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NEW YORK

AERONAUTICAL METEOROLOGY

By

WILLIS RAY GREGG, A.B.

Meteorologist, U. S. Weather Bureau; Fellow, American Meteorological Society; Fellow, Royal Meteorological Society

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EDITORIAL PREFACE

Rudyard Kipling has been quoted as saying of aerial navigation: "We are at the opening verse of the opening page of the chapter of endless possibilities." No longer is there doubt as to the practicability of flying. That was demonstrated by the United States Air Mail; the commercial airlines in Europe and South America; the crossings of the Atlantic Ocean by airplanes, seaplanes and airships; and finally the circumnavigation of the earth by airplane.

While the consequences to flow from man's new power cannot yet be estimated, of this we may be certain: As the development within a few generations of railway, steamship, and automobile has altered every relation of the world's life, so the possession at last of aircraft, enabling us to utilize the free and universal highway provided by nature, must lead to effects upon human activity no less wide and profound.

The need is widely felt already for a progressive literature of aerial navigation. We need technical information for designers, engineers, and pilots and for the growing army of students. We need also discussions of the practical implications of air navigation, for statesmen, economists, and representatives of industrial and commercial organizations whose interests and operations are affected by the new mode of transit. The Ronald Aeronautic Library, a series of volumes by specialists able to speak with authority, supplies this information. It is the purpose of the editor to keep the Library continually abreast of every phase of aerial development.

The division into separate volumes is governed by the needs of each branch of aeronautics. At the same time this permits of frequent revisions to keep pace with the progress of an ex-

panding art. The arrangement of the text facilitates reference almost to the extent found in the standard engineering handbooks. Information is not limited to American experience; foreign sources are drawn upon freely.

C. DEF. CHANDLER,
Editor, Ronald Aeronautic Library

AUTHOR'S PREFACE

An intimate knowledge of the characteristics of the atmosphere is generally recognized as indispensable to the successful development of aeronautics. The aeronautical engineer must have at his command information regarding variations in density, pressure and temperature with height. The promoter of air lines can determine and guarantee workable schedules only if he has detailed data on wind and weather conditions along the proposed airways, particularly the frequency and strength of head and cross winds. Insurance companies cannot fix suitable premium rates without information as to the frequency of unfavorable weather conditions such as fogs, thunderstorms, excessive precipitation, etc. The pilot should know the variation in direction and velocity of winds with change in altitude; the frequency of winds of different directions and velocities at various altitudes; the principal causes of gustiness; the size and other characteristics of thunderstorms; the average height of the different types of clouds; the main characteristics of cyclones and anticyclones; and many other details of the "air and its ways." He should have a knowledge of the significance of changes in pressure, wind and cloud formation and through this knowledge be able to amplify and interpret locally the more general forecasts received for a wider territory. In fine, his grasp of the subject should be such as to enable him to derive the greatest possible advantage from every condition of wind and weather that he may meet.

The purpose of "Aeronautical Meteorology" is to supply these needs, to give in concise "handbook" form the essential facts of the upper air and to point out their relation to the development and safety of aeronautics. So far as known it is the only work of its kind in the English language embodying the results of the most recent aerological research. There are

in existence many excellent treatises on general meteorology, but these naturally do not contain the detailed information most needed by the airman and on the other hand do contain much material of interest only to the professional meteorologist. In "Aeronautical Meteorology" this latter type of information has been included only so far as to provide a general groundwork for the better understanding of atmospheric processes and conditions directly related to aeronautics.

In the preparation of this book the author has profited from the advice and encouragement of Prof. C. F. Marvin, Chief of the U. S. Weather Bureau. Grateful acknowledgment is also due the following Weather Bureau officials who read the manuscript and offered many helpful suggestions: Dr. W. J. Humphreys, Prof. A. J. Henry, and Messrs. V. E. Jakl, C. L. Mitchell, L. T. Samuels and R. H. Weightman. Reference to others who furnished assistance in the preparation of certain sections is made at appropriate places in the text.

WILLIS RAY GREGG.

Washington, D.C.,
October 10, 1925.

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AERONAUTICAL
METEOROLOGY

INTRODUCTION

The chief constituents of the atmosphere are nitrogen and oxygen. The other permanent gases that occur in appreciable amounts are argon, hydrogen, neon, helium and carbon dioxide. According to Humphreys [1] the percentage distribution of these gases by volume in dry air at sea level is as follows:

Nitrogen	78.03	Neon	0.0012
Oxygen	20.99	Helium	0.0004
Argon	0.94	Carbon dioxide	0.03
Hydrogen	0.01		

Among those that occur in mere traces are krypton, xenon, ammonia and sulphur dioxide. In addition to the above there is always water vapor of varying amount, depending upon the season, location, temperature and other conditions. On the average it constitutes about 1.2% of the atmosphere at the earth's surface, and the percentages of nitrogen and oxygen are then changed from those given in the table to 77.08 and 20.75 respectively.

It is important to recognize that the atmosphere is a mechanical mixture, not a chemical compound. Nevertheless its composition at the surface remains remarkably constant the world over.

There is little variation also in the lower 10 to 12 kilometers of the atmosphere, owing to convective mixing.[2] At greater heights it is probable that the gases are arranged according to their molecular weights, and therefore that above 100 kilometers hydrogen may constitute nearly 100% of the atmosphere. Definite data on this point are lacking, however.

[1] "Physics of the Air."
[2] For discussion of convection see page 7.

Height of the atmosphere. Observations of meteors and auroras indicate that the atmosphere extends at least to 300 kilometers; how much farther is as yet purely conjectural.

The principal meteorological elements are pressure, temperature, moisture, cloudiness, precipitation, sunshine, wind direction and speed, and visibility.

Weather is the state of these elements at a given time and place, or during a particular period and in a specified region.

Climate is the normal state of these elements for a period of years, the longer this period, the better. Means, mean maxima and minima, frequencies of certain values or conditions, etc., absolute extremes, for the hour, day, week, month, season and year are properly included in a complete picture of the climate of a place or region.

Meteorology is the science of the earth's atmosphere, embracing therefore both weather and climate. The study of the latter, however, is separately designated **climatology.** Another branch of meteorology which has received much attention during the past 30 years is **aerology,** the study of the upper, or free, air.

With the introduction of scientific methods in industry and commerce, applied meteorology has of recent years rapidly come to the front and thus we have such subdivisions as **aeronautical, marine, agricultural,** and **insurance meteorology.**

Aeronautical meteorology is that branch of meteorology which deals with the practical application of what is known of the atmosphere to the needs of aeronauts and aviators. This is the branch or subdivision upon which emphasis will be placed in this book. Most attention will moreover be paid to conditions in the United States, but in order to provide a suitable back-

ground for their better understanding a very brief outline of world meteorology is given in Chapter I.

Units and abbreviations. In the United States English units and the Fahrenheit temperature scale are used for surface observations, because they are the official standards for this country and are in general use by the public. For the free-air observations metric units and the centigrade temperature scale are used, in order to make the data more readily comparable with those of most other countries. Conversion tables are given in Appendix IV. Abbreviations in common use are as follows:

ELEMENT	UNIT	ABBREVIATION
Pressure [Barometric (P) and Vapor (e)]	Inch (mercury)	in.
	Millimeter (mercury)	mm.
	Millibar	mb.
Temperature (t)	Fahrenheit	°F.
	Centigrade	°C.
Relative humidity	Per cent	%
Absolute humidity	Grains per cubic foot	gr./cu. ft.
	Grams per cubic meter	g/cu. m. or g/m.^{3}
Precipitation	Inch	in.
	Millimeter	mm.
Density (ρ)[a]	Pounds per cubic foot	lb/cu. ft.
	Grams per cubic centimeter	g/c. c.
	Kilograms per cubic meter	kg/cu. m. or kg/m.^{3}
Wind velocity (v)	Miles per hour	m. p. h.
	Feet per second	ft./sec.
	Meters per second	m. p. s. or m/s.
	Kilometers per hour	Km./hr.
Altitude (z or h) and distance	Foot	ft.
	Meter	m.
	Mile	mi.
	Kilometer	Km.

[a] Strictly speaking, density is the mass per unit volume, i.e., $\rho = \frac{\omega}{g}$. In common practice, however (e.g., in Smithsonian Meteorological Tables) it has been used to express weight per unit volume, and this use is adhered to in the following sections.

CHAPTER I

GENERAL CIRCULATION OF THE ATMOSPHERE

Temperature. For all practical purposes insolation, or the sun's radiant energy, may be said to be entirely responsible for the heat of the earth's atmosphere, that from the interior of the earth and from heavenly bodies other than the sun being negligible.

The amount of insolation received by the earth as a whole varies about 7% during the year owing to the eccentricity of the earth's orbit. The time of nearest approach of earth to sun is about January 1 and that of greatest distance about July 1. Thus, the earth as a whole receives most heat during winter of the northern hemisphere and least during summer.

The earth's axis is inclined 66½° to the plane of the ecliptic and always remains parallel to itself as the earth revolves around the sun. The change thus brought about in the presentation of the earth to the sun causes an apparent migration of the latter through 47° from the Tropic of Cancer on June 21 to the Tropic of Capricorn on December 21. This migration gives rise to three important results: (1) The thermal equator, as distinguished from the geographical equator, moves northward and southward with the sun and materially affects the general planetary circulation; (2) the sun's rays fall more and more obliquely on the surface of the northern hemisphere, as the sun moves southward (and vice versa in the southern hemisphere), thus varying the amount of energy per unit of surface, not only because these rays are spread out more as their angle of incidence diminishes, but also because somewhat greater absorption occurs by reason of their longer path through the atmosphere; (3) the relative

lengths of day and night change greatly throughout the year. The following table shows the length of the longest day (hence also of the longest night) at certain latitudes:

Latitude	0°	17°	41°	49°	63°
Duration	12 hr.	13 hr.	15 hr.	16 hr.	20 hr.
Latitude	66½°	67° 21′	69° 51′	78° 11′	90°
Duration	24 hr.	1 mo.	2 mo.	4 mo.	6 mo.

According to Abbot and Fowle about 37% of the insolation intercepted by the earth is reflected by clouds and by the earth's surface and atmosphere. Most of the remaining 63% is transmitted by the atmosphere directly to the surface, although a small amount is absorbed by water vapor, carbon dioxide and ozone. Much of the insolation that reaches the earth's surface is there absorbed and re-radiated as terrestrial radiation, long wave-length, which is more readily absorbed by the atmosphere than is the short wave-length solar radiation. The extent of the absorption depends upon the amount of water vapor present and therefore varies greatly from time to time in its effect at various levels. Air in contact with the earth's surface is heated or cooled by conduction. If it is heated, its density diminishes and it is forced by denser air above it or adjacent to it to ascend. This process is called **convection** and is one of the most important agencies in determining both the vertical and the horizontal distribution of temperature over the earth.

Land and water areas exercise another marked influence upon temperature distribution. Water surfaces reflect about 40% of the insolation reaching them. The remainder is transmitted to lower depths and absorbed, but much of it is used in evaporating the water and is therefore stored up as latent heat. The result is that water surfaces and the air in contact with them maintain a relatively constant temperature. Land areas, on the other hand, reflect and transmit very little insolation and there is much less evaporation. The specific heat of land is low; hence, land areas become strongly heated during insolation and similarly cooled in its absence.

The temperature distribution over the globe is in large part the result of the influences and conditions briefly outlined in the foregoing paragraphs. Isothermal charts for summer and winter show: (a) the migration of the thermal equator and the shifting of climatic zones; (b) the crowding together of isotherms in winter and the relatively large distances between them in summer; and (c) the bending of isotherms over land areas poleward in summer and equatorward in winter.

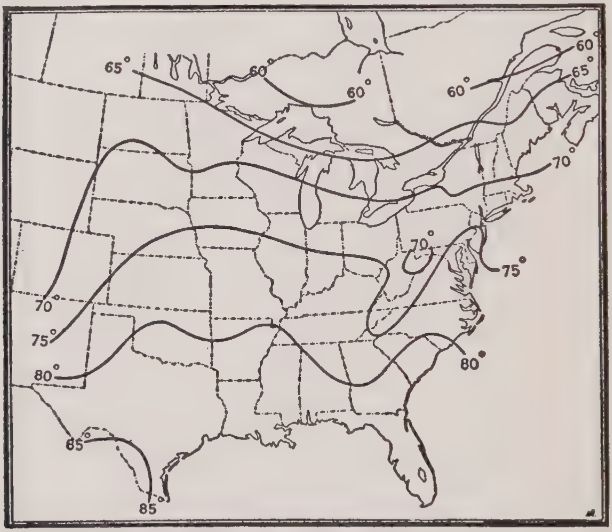


Figure 1. Average July Temperatures, °F., in the United States, East of the Rocky Mountains

Figures 1 and 2 give average July and January temperatures for the United States east of the Rocky Mountains. Farther west the latitudinal change is largely obliterated by topographic irregularities. These two months are, in most parts of the northern hemisphere, the hottest and coldest respectively; in other words, the temperature lags behind the times of greatest and least heat received from the sun. This is true because, in early summer the atmosphere is still cool from the effects of the preceding winter and in northern

regions snow covers the ground until late spring. Much of the sun's heat is required to overcome these influences. When this has been accomplished, the effect of insolation increases for a time, even though the amount received is less than before. In winter the opposite of this occurs.

Similarly, there is a lag in the daily temperature march, the highest occurring between 2 and 4 P.M., and the lowest about the time of sunrise.

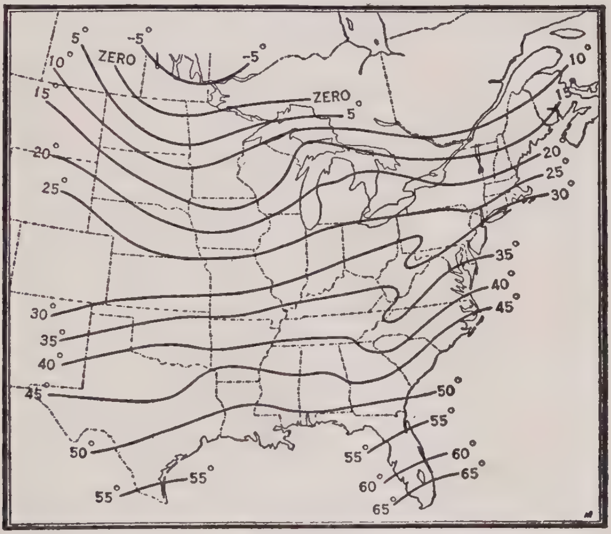


Figure 2. Average January Temperatures, °F., in the United States, East of the Rocky Mountains

Pressure and wind. The causes of temperature distribution over the earth have been given in some detail, because of the intimate relation between temperature on the one hand and pressure and wind on the other. Changes in temperature produce changes in density which set up vertical movements resulting in changes in pressure. Horizontal air movement, or wind, represents Nature's effort to adjust these changes in pressure. Since the equatorial regions receive most heat and the polar regions least heat one would at first suppose that

pressures would be lowest in the former and gradually increase to a maximum in the latter. This is what would occur on a non-rotating earth. Because of the earth's rotation, however, the overflowing air from the tropics is deflected to the right in the northern hemisphere and to the left in the southern hemisphere by a force, d, defined in the equation

$$d = 2\ m\omega v \sin l,$$

in which m is the mass of the body acted upon, v its speed, l its latitude, and ω the angular velocity of the earth's rotation $\left(\frac{2\pi}{86{,}164}\right)$ (more exactly, it would require such a force to prevent deflection). The value of d is zero at the equator, but increases to $2\ m\omega v$ at the poles.

The ultimate result of the two influences, viz., decreasing temperatures from equator to poles and deflective effect of the earth's rotation, is a pressure distribution as follows:

Doldrums, a belt of low pressure in the tropics, closely following the thermal equator, and characterized by light winds and calms, heavy rains and thunderstorms.

Horse latitudes are belts of high pressure at about latitude 30° N and S, migrating with the sun and characterized by fine, clear weather and little air movement.

Pressure diminishes on either side of the horse latitudes, resulting in wind systems known as the trade winds on the equatorial side and the prevailing westerlies on the poleward side.

Trade winds, northeast in the northern hemisphere and southeast in the southern, blow fairly continuously over the oceans, especially the Atlantic, from about latitude 30° to the doldrums. According to Hann the average limits of the trade winds and the doldrums on the Atlantic are as follows:

	Summer	Winter
N. E. Trades	35° N–11° N	26° N– 3° N
Doldrums	11° N– 3° N	3° N– 0°
S. E. Trades	3° N–25° S	0° –25° S

The east component in these winds results from the deflective effect of the earth's rotation. As they approach the doldrums, the air rises and forms a southwest wind (northwest in southern hemisphere) known as the antitrade. The depth of the trades varies considerably, but in general is greatest during summer and least during winter and decreases from 10 or 12 kilometers near the equator to zero at about latitude 30°. Weather is generally fair, with some cloudiness but little precipitation. According to Sir Napier Shaw, the average velocities of the Atlantic trade winds are as follows, values being given in miles per hour:

	Jan.	Feb.	Mar.	Apr.	May	June
N. E. Trade	10	11	11	12	11	10
S. E. Trade	14	13	13	12	11	12

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
N. E. Trade	9	7	8	6	8	10	9
S. E. Trade	12	15	17	15	16	15	14

The Pacific trade winds are weaker and less constant in direction; on the Indian Ocean they are confined to the southern hemisphere.

Prevailing westerlies. Poleward from the horse latitudes there is a decrease of pressure, small in amount at sea level but increasing rapidly in the upper levels. As a result of this pressure distribution the winds throughout temperate latitudes are prevailingly from a westerly quarter. They are far from possessing the characteristics of the trade winds, however, the latter blowing almost constantly from the same direction, whereas the prevailing westerlies are frequently interrupted by passing areas of high and low pressure. They are better developed in the southern than in the northern hemisphere, in the winter than in the summer half of the year and in the upper than in the lower levels.

As in the distribution of temperature, so in that of pressure there are many irregularities caused by land and water areas

and these irregularities greatly modify the general circulation. For example, the horse latitudes and the trade winds are best developed over the oceans, and the prevailing westerlies in the southern hemisphere (there known as the "roaring forties") because of freedom from continental obstructions. There is also a seasonal shifting of "centers of action," i.e., more or less permanent areas of high or low pressure, between continents and oceans, purely a temperature effect, of course. The interior of Asia has the largest range, the summer average being about 1,000 mb. (29.5 in.) and the winter about 1,035 mb. (30.5 in.).

Figure 3. Prevailing Winds in the United States during July (after Ward)

Monsoons. The monsoon tendency, i.e., landward winds in summer and seaward in winter, exists along all coast lines, but is best developed in the southern part of Asia, owing to the large seasonal pressure range, above cited. The average depth of the winter northeast monsoon of India is about 2,000 meters, and that of the summer southwest monsoon about 5,000 meters, although there is considerable variation with latitude. The southwest monsoon is in general more pronounced than the

northeast, and is intimately related to the economic life of India. Strictly speaking, however, the monsoons are not part of the *general* circulation.

In the United States the chief monsoon effects are in the eastern portion, where the prevailing winds are northwest in

Figure 4. Prevailing Winds in the United States during January (after Ward)

winter and southwest in summer; and in Texas, where they are also northwest in winter, but southeast in summer, as shown in Figures 3 and 4.[1]

[1] "The Prevailing Winds of the United States," by Robert DeC. Ward, ***Annals of the Association of American Geographers,*** Vol. 6, pp. 99-119, 1916. Abstract in *Monthly Weather Review,* Vol. 47, pp. 575-576, August, 1919.

CHAPTER II

INSTRUMENTS AND METHODS OF OBSERVATION

Observations are of two kinds—instrumental and non-instrumental. Instruments are also of two kinds—direct, or eye-reading; and automatic or recording. Such phenomena as the state of the weather, visibility, the kind and amount of clouds, the beginning, ending, intensity and location of thunderstorms, tornadoes, etc., are observed without the aid of instruments. Observations of pressure, temperature, humidity, speed of cloud movement, wind velocity, duration of sunshine and intensity of solar radiation are made by means of instruments. Direction of cloud movement and wind direction are observed by both methods.

Beaufort scale of wind force. In some cases, particularly at sea, wind velocity or force is estimated non-instrumentally in accordance with the scale proposed by Admiral Beaufort in 1805. It was based upon the effects produced by various wind speeds on water craft, but it was later adapted for use on land also. It consists of 13 groups, 0 to 12 inclusive, and the designation or specification and the equivalent limiting wind speeds of these groups as adopted in the United States and Great Britain are given in the tabulation on page 15.

Instruments and other apparatus used by meteorological services are described in detail in various publications.[1] Only brief reference to those most closely related to aeronautics will be made here.

[1] An excellent, copiously illustrated, monograph on this general subject has recently appeared under the title, "Meteorological Instruments and Apparatus Employed by the United States Weather Bureau," by Roy N. Covert, published in *Journal of the Optical Society of America and Review of Scientific Instruments,* Vol. 10, No. 3, pp. 299-425, March, 1925.

Beaufort Scale of Wind Force

Beaufort number	Explanatory titles	Mode of estimating aboard sailing vessels	Specifications for use on land	Miles per hour (statute)	Terms used in U. S. Weather Bureau forecasts
0	Calm		Calm, smoke rises vertically.	Less than 1	Light
1	Light air	Sufficient wind for working ship	Direction of wind shown by smoke drift, but not by wind vanes.	1–3	
2	Slight breeze		Wind felt on face; leaves rustle; ordinary vane moved by wind.	4–7	
3	Gentle breeze		Leaves and small twigs in constant motion; wind extends light flag.	8–12	Gentle
4	Moderate breeze	Forces most advantageous for sailing with leading wind and all sail drawing	Raises dust and loose paper; small branches are moved.	13–18	Moderate
5	Fresh breeze		Small trees in leaf begin to sway; crested wavelets form on inland waters.	19–24	Fresh
6	Strong breeze	Reduction of sail necessary with leading wind	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	25–31	Strong
7	High wind		Whole trees in motion; inconvenience felt in walking against wind.	32–38	
8	Gale	Considerable reduction of sail necessary even with wind quartering	Breaks twigs off trees; generally impedes progress.	39–46	Gale
9	Strong gale		Slight structural damage occurs (chimney pots and slate removed).	47–54	
10	Whole gale	Close reefed sail running, or hove to under storm sail	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	55–63	Whole gale
11	Storm		Very rarely experienced; accompanied by widespread damage.	64–75	
12	Hurricane	No sail can stand even when running	....	Above 75	Hurricane

Surface Instruments

Barometers are of 2 types, mercurial and aneroid. The mercurial barometer is essentially a glass tube about 3 feet in length, with one end closed and the other immersed in a cistern of mercury. The height of the column, corrected for temperature and gravity, gives the pressure in inches, millimeters or millibars, according to the units employed. The aneroid barometer is less accurate than the mercurial but has the advantage of being more readily carried from place to place. It consists of a thin-walled, air-tight metal box which changes its shape with changes in pressure, the movements being communicated by suitable levers to an index above a circular dial. Aneroids should be compared occasionally with a mercurial barometer as a precaution against creep or lag, and against a change of zero.

Barographs are also of the mercurial and aneroid types. The mercurial, when properly made, gives an extremely accurate record, but its construction is complicated, and very few therefore are in use. The aneroid barograph differs from the barometer in that the movements induced by pressure changes are communicated to a recording pen instead of to a pointer. The pen traces the record on graduated paper mounted on a clock-driven cylinder.

Thermometers. Air temperatures are usually measured by means of changes in volume of mercury or other liquid having a large coefficient of expansion. Alcohol is generally used in minimum thermometers; also, in places where temperatures below the freezing point of mercury occur. Maximum and minimum thermometers give the extremes between settings, but do not indicate their time of occurrence or other changes. Electrical resistance thermometers are seldom used in meteorological observations, except for calibrating meteorographs designed for sounding balloon work.

Thermographs are self-recording thermometers usually consisting of a "Bourdon" tube or a bimetallic spiral, the other features of the instruments being similar to those of barographs. Large spirit thermometers with floats, and mercury thermometers arranged to record photographically have been developed, but are less satisfactory than the usual type.

Psychrometers in general use consist of two ordinary thermometers, mounted together, with the bulb of one covered with muslin or other similar fabric, which is moistened before an observation. Cooling of the wet bulb thermometer by evaporation is produced either by rapid whirling or by a small clock-driven fan, as in the Assmann aspiration psychrometer. The readings of the two thermometers make possible, by means of tables based on experiments, the quick determination of the relative and absolute humidity, vapor pressure and dew point. At temperatures near and below freezing care is necessary in obtaining the correct depression, owing to the setting free of latent heat when the water freezes.

Hygrometers indicate the relative humidity of the atmosphere through the expansion and contraction of a bundle of human hairs or several hairs separately mounted, the movements being communicated to a pointer moving above a graduated dial. Frequent comparisons with standard instruments are necessary owing to the uncertain change of zero.

Hygrographs also depend upon the effect of moisture upon human hair, the changes in this case being communicated to a recording pen instead of a pointer.

Anemometers are of two general types—rotation and pressure. The former are in most common use and consist either of systems of cups (Robinson type) or fans (windmill type). The latter indicate the pressure of the wind upon a flat surface of known area or upon liquid in a manometer. The Pitot tube and the Dines anemometer are good examples of this

type. They are superior to the cup or windmill instruments when records of gustiness, i.e., extreme velocities are desired.

Wind vanes, or **anemoscopes** indicate the direction from which the wind is blowing. They vary in length, but those most commonly used are 4 feet and 6 feet.

Rain gages. For greatest accuracy the rainfall caught in a metal cylinder, suitably exposed, is measured in a much smaller tube, usually one having one tenth the cross-section of the receiver. Many gages are provided with a bucket, mounted underneath the receiving funnel and so balanced as to tip when a certain amount has run into it.

Snow gages give the depth and water content of snow and sleet falls. In the case of snow, however, greater accuracy is realized by cutting a section of known area at some place on the ground or roof where no drifting has occurred.

Sunshine recorders as a rule record only the duration of sunshine, but some indicate its intensity also. The one in common use in this country records duration through electrical contact made by the movement of mercury in the stem of a vacuum-enclosed black bulb differential air thermometer. Others operate by charring on a strip of cardboard through a spherical lens, or by photographic traces on sensitized paper.

Quadruple register is a combination recording mechanism, in regular use in the Weather Bureau, whereby a continuous 24-hour record of wind direction and velocity, rainfall and sunshine is made on one sheet of paper moved by clockwork. The recording pens are electrically connected with the wind vane, anemometer, tipping bucket rain gage and sunshine recorder. One pen records both rain and sunshine, since the two seldom occur together.

Nephoscopes are used in measuring the movements of clouds. The most recently designed pattern consists essentially of a black mirror mounted in a circular frame graduated in

degrees and a movable sighting eyepiece stand. For observations the face of the mirror must be absolutely level. Direction of cloud movement can be determined accurately; also the speed, if the altitude is known.

Aerological Instruments and Apparatus

The principal means of free-air investigation at present employed are kites, pilot balloons, sounding balloons and airplanes. In the past much valuable information has also been obtained by triangulation measurements of cloud heights and movements and by observations in free and captive balloons.

Kites of the box type, designed by Hargrave and modified by Marvin, have been found most satisfactory for all-round use, as they possess stability in flight and are capable of reaching a good average altitude. They are about 7 feet square and 3 feet in height, made of straight-grained spruce framework, suitably guyed with wire braces and covered with a good grade of cotton cloth. The main line used in kite flying is piano steel (music) wire of small diameter but high tensile strength, and this wire is paid out from a steel drum which is operated by a variable speed motor, the entire apparatus being housed in a small circular building so mounted on a turntable that it can be easily turned in any direction, according to the wind conditions prevailing at the time. As a rule several kites are used in tandem in order to lift the wire. The average height reached by kites is between 2½ and 3 kilometers, and the greatest height in this country, 7¼ kilometers.

Kite meteorographs, to be most efficient, must be light, compact, durable and accurate. Several types have been introduced, but the most satisfactory in many respects and the one in regular use in this country is that designed by C. F. Marvin. The essential features of this instrument are a light, rigid tube and a framework, firmly united, which serve as sup-

ports for the several recording devices and provide satisfactory exposure for the sensitive elements. The windmill anemometer, bimetallic temperature element and hygrometer hairs are mounted inside the tube and the aneroid is secured to the frame, which also carries the clock-driven cylinder on which the records are made. The meteorograph is so mounted in the kite that the wind blows directly through the tube, thus operating the anemometer and providing ventilation for the temperature and humidity elements.

Sounding balloons are used in explorations of the air at heights above those attainable by kites, airplanes, etc. They are made of pure rubber and filled with sufficient hydrogen to cause them to ascend at a rate of 200 to 300 m. p. m. (meters per minute) thus providing good ventilation for the instruments. Sounding balloons are used singly or in pairs. In the former case a parachute lets down the instrument after the balloon bursts; in the latter, one of the balloons bursts and the other lets the instrument down slowly. Important researches have been conducted with these balloons, though they have been little used since the World War. Heights above 30 kilometers have been reached in some instances.

Sounding balloon meteorographs are similar in principle to those used in kites, but are lighter, adapted to vertical rather than horizontal ventilation and carry no anemometer. Also, because of the excessively low temperatures often experienced, the record is made by a metal stylus on a smoked sheet instead of by ink on paper.

Pilot balloons constitute in many respects the most practicable means of free-air investigation, but their use is limited to clear weather or at any rate to the region beneath cloud layers, and they furnish information only as to wind conditions and height and movement of clouds. Like sounding balloons, they are made of pure rubber but they are much smaller, the most common size, uninflated, being 6 inches in diameter.

Other sizes more or less used are 7½ and 9 inches in diameter. The 6 inch balloon weighs from 20 to 35 grams. When inflated for an ascension it has a diameter of about 28 to 30 inches, and a free lift or buoyancy that results in a rate of ascent of about 180 to 200 m. p. m. The balloons reach varying heights depending upon their quality. They are frequently observed as high as 5 kilometers, occasionally as high as 10 kilometers, and in two instances at least above 15 kilometers.

Theodolite. This is one of the most important instruments in aerological investigations, being used with kites and with both types of balloons. Its principal features are a horizontal and a vertical circle, each with a vernier, and a telescope of the bent axis type, the incoming rays being diverted into the transit axis by means of a right-angle prism. This device prevents the fatigue which would otherwise result from long observing with an ordinary transit. Two theodolites at the ends of a measured base line are used for determining the heights of pilot balloons, as a check on those assumed from an empirical equation; they are also used occasionally with kites and sounding balloons as a check on the altitudes computed from the pressure and temperature records. For the most part, however, one theodolite only is used. In either case, with the balloons moving freely in the air, the readings of the theodolite's horizontal and vertical circles together with the height, assumed or computed, make possible the determination of the balloon's horizontal distance from the observation point and its position relative to a north-south or other reference line. With these data available for successive time intervals, the wind direction and speed at various heights are readily computed by the slide rule, logarithmic or plotting board method.

Airplanes have been used more or less in free-air observations, and it seems likely that such use will very largely increase, and that other forms of aircraft, particularly airships, will be similarly employed. Aside from measurements of tempera-

ture, pressure and moisture, observations of visibility, both vertical and horizontal, sky brightness, dust content, close-up views of clouds, etc., can be taken and will undoubtedly very materially extend our knowledge of meteorological conditions and processes. The full utilization of these agencies awaits only the development of suitable apparatus and an organization to direct and co-ordinate the work.

CHAPTER III

VERTICAL STRUCTURE OF THE ATMOSPHERE

Troposphere and Stratosphere. A vertical section of the atmosphere from the equator to either pole would show, as its most distinctive feature, a marked contrast between the lowest 10 to 15 kilometers and the region above those levels, with a sharp line of demarcation between the two. The lower region is known as the *troposphere* and the upper, as the *stratosphere.* The troposphere is characterized in general by decreasing temperatures with altitude, amounting on the average to 6° C. per kilometer and by considerable cloudiness; the stratosphere, by little vertical change in temperature and by no cloudiness. The height of the dividing line, sometimes called the *"tropopause,"* varies from about 17 kilometers in the tropics to about 8 or 9 in the polar regions; in the United States and Europe it is between 11 and 12. It is also greater in summer than in winter and above high than above low surface pressure. The temperature of the stratosphere varies inversely with the height of its base, being lowest, about –80° C., over the tropics, and increasing to about –55° C. in latitudes 40° to 50°; also it is lower above high than above low surface pressure.

Interest in the stratosphere, so far as aeronautics is concerned, is, at the present time at least, largely academic. In the following sections attention will be confined for the most part to the troposphere, particularly to the lowest 5 kilometers.

Temperature. As already stated, the normal change of temperature with altitude in the troposphere is a decrease, generally called "lapse rate," amounting to about 6° C. per kilometer

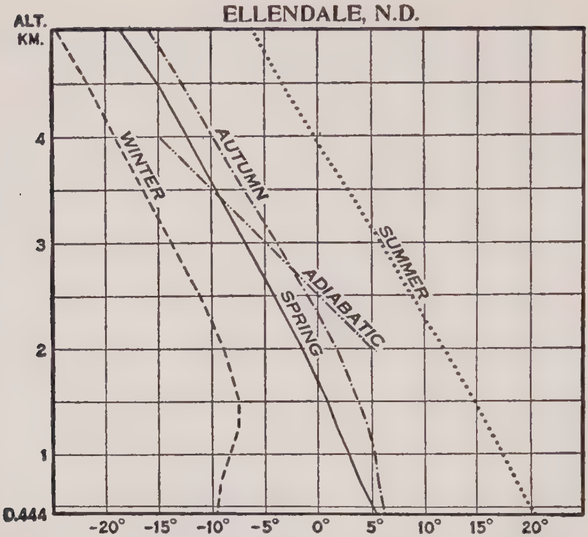


Figure 5. Average Seasonal Free-air Temperatures, °C., at Ellendale, North Dakota

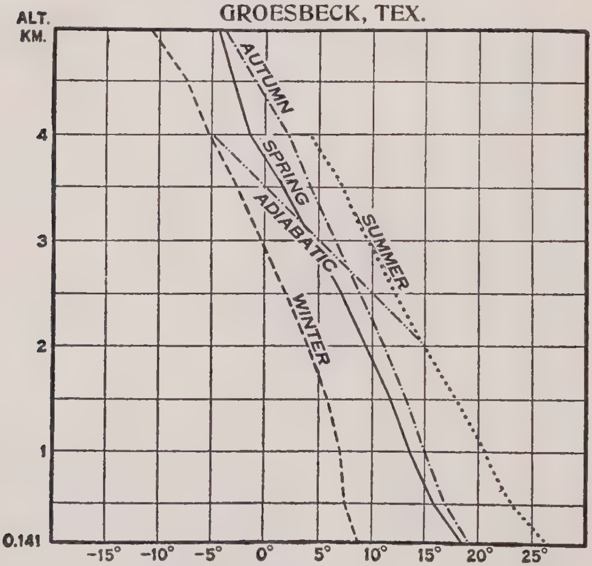


Figure 6. Average Seasonal Free-air Temperatures, °C., at Groesbeck, Texas

in all parts of the world. It is largest, about 7° C., between 5 and 10 kilometers and in this region it is quite uniform throughout the year and from day to day. In the lowest 5 kilometers it amounts to about 5° C., but is exceedingly irregular, varying from a strongly inverted condition (increase with altitude) to slightly above the dry air adiabatic rate (1°C. per 100 meters).

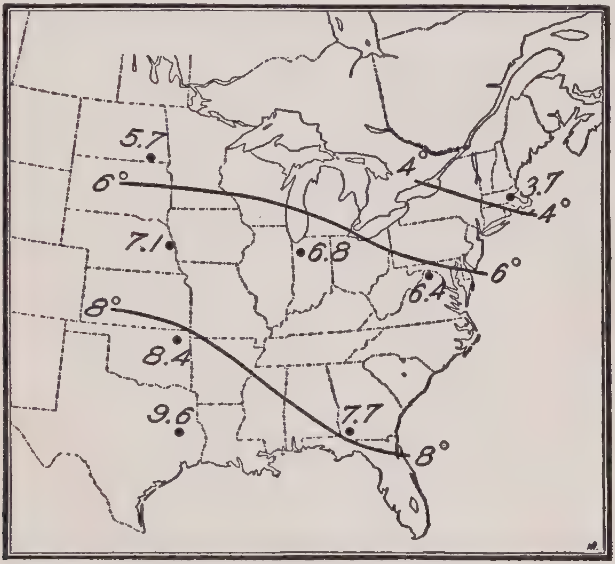


Figure 7. Average Summer Temperatures, °C., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

The latter condition occurs only for brief periods and through short intervals of altitude, usually in the hottest part of the day and immediately above the surface. Inversions are most pronounced when net loss by radiation is large, as at night or in the interior of continents during winter. They also occur as the result of importation of warm air above cold and the underrunning of cold currents at the surface, owing to different wind directions at various levels and as a result of strong surface winds. Figures 5 and 6 show the average seasonal lapse

rates at Ellendale, N. D., and Groesbeck, Tex. These also indicate the greater annual range at all levels in the northern part of the country than in the southern, as well as the rather small decrease in this range from the surface up to 5 kilometers.

The latitudinal range in temperature at the surface for summer and winter has already been shown in Figures 1 and 2 (pages 8, 9). That a similar marked difference persists at upper

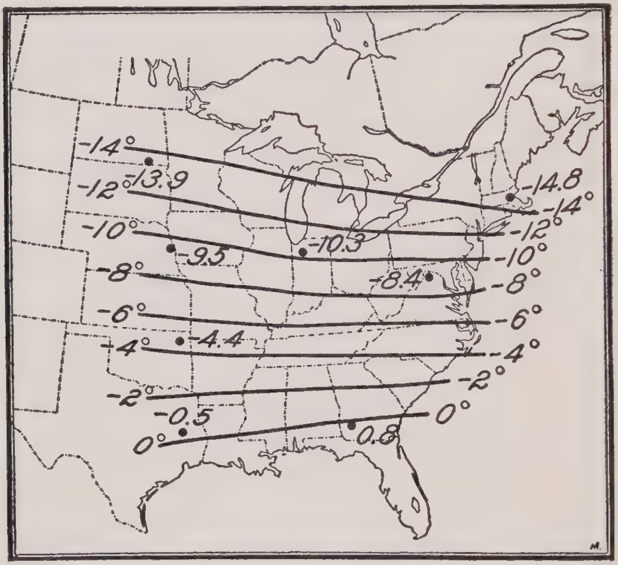


Figure 8. Average Winter Temperatures, °C., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

levels is indicated in Figures 7 and 8. Close relationship exists between these gradients and the seasonal differences in strength of winds, as will be shown later, (Figures 30 and 31).

The highest and lowest temperatures ever recorded at different levels in summer and winter at these two stations are given in Table 1. These figures indicate that, even in the northern part of the United States, temperatures at ordinary flying levels seldom reach the freezing point in summer and are little lower than those at the surface in winter.

TABLE I.—HIGHEST AND LOWEST TEMPERATURE, °C., IN SUMMER AND WINTER AT ELLENDALE, N. DAK. AND GROESBECK, TEX.

ELLENDALE, N. DAK.

Altitude M. S. L.* m.	Summer		Winter	
	Highest	Lowest	Highest	Lowest
444 (surface)	34.0	8.1	10.9	−31.3
500	33.4	7.8	10.6	−30.8
1,000	29.4	4.0	12.8	−33.7
2,000	25.7	−2.6	9.8	−33.6
3,000	18.0	−6.8	3.6	−36.8
4,000	10.2	−9.4	−3.4	−30.8
5,000	2.2	−12.6	−17.0	−35.6

GROESBECK, TEX.

Altitude M. S. L.* m.	Summer Highest	Summer Lowest	Winter Highest	Winter Lowest
141 (surface)	35.6	12.8	26.4	−7.0
500	31.8	10.8	22.8	−9.4
1,000	26.8	8.4	22.4	−9.2
2,000	19.6	4.8	17.2	−11.6
3,000	14.8	0.6	11.2	−14.6
4,000	8.6	−4.4	5.1	−13.1
5,000	....	......	−3.9	−18.4

* M. S. L. is an abbreviation for Mean Sea Level.

The diurnal range of temperature, characteristic of the surface, disappears almost altogether at 1 to 1½ kilometers. Above that level the phase remains nearly the same as at the surface, but the amplitude is very small, averaging about 1° C.

Altitude M. S. L. m.	Summer			Winter		
	Time of Highest	Time of Lowest	Range °C.	Time of Highest	Time of Lowest	Range °C.
396 (surface)	4 P.M.	5 A.M.	10.7	3 P.M.	7 A.M.	7.9
500	4 P.M.	5 A.M.	8.1	3 P.M.	8 A.M.	5.1
750	5 P.M.	8 A.M.	4.8	4 P.M.	9 A.M.	1.8
1,000	6 P.M.	9 A.M.	3.2	5 P.M.	10 A.M.	1.3
1,500	7 P.M.	8 A.M.	1.0	5 P.M.	12 M.	0.6
2,000	6 P.M.	6 A.M.	0.7	5 P.M.	4 A.M.	1.1
2,500	7 P.M.	6 A.M.	0.9	5 P.M.	6 A.M.	1.4
3,000	7 P.M.	9 A.M.	0.6	2 P.M.	2 A.M.	1.1
3,500	10 P.M.	2 P.M.	0.5	9 P.M.	7 A.M.	1.0

The preceding gives the times of occurrence of highest and lowest and the daily range above Drexel, Neb.

Humidity. Absolute humidity is the actual amount of water vapor in the air. The total possible amount, i.e., at saturation, increases rapidly with temperature. For example, the weight at 0° C. is 4.8 grams per cubic meter; at 15°, 12.8 grams; and at 30°, 30.4 grams. Absolute humidity is often expressed in terms of the expansive force that the vapor exerts

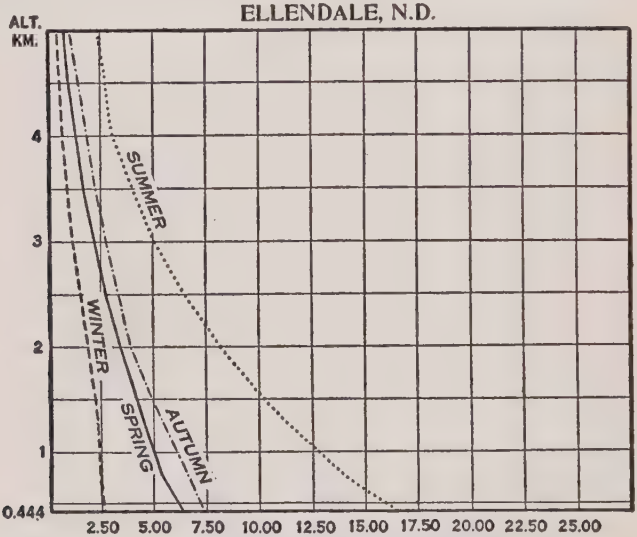


Figure 9. Mean Seasonal Free-air Vapor Pressures, mb., at Ellendale, N. D.

and is then referred to as **vapor pressure,** measured in the same units employed for barometric pressure. **Relative humidity** is the amount of water vapor present at any one time as compared with the amount at saturation and is expressed as a percentage. Relative humidity is very irregular, but on the average decreases from about 70% at the surface to about 50% at 4 or 5 kilometers. In general it is higher in

the southern states than in the northern during summer and vice versa during winter.

Since vapor pressure varies with the temperature and relative humidity, both of which decrease with altitude on the average, its change with altitude is also a sharp decrease in summer and a more moderate one in winter; this decrease is more pronounced in all seasons in the southern than in the

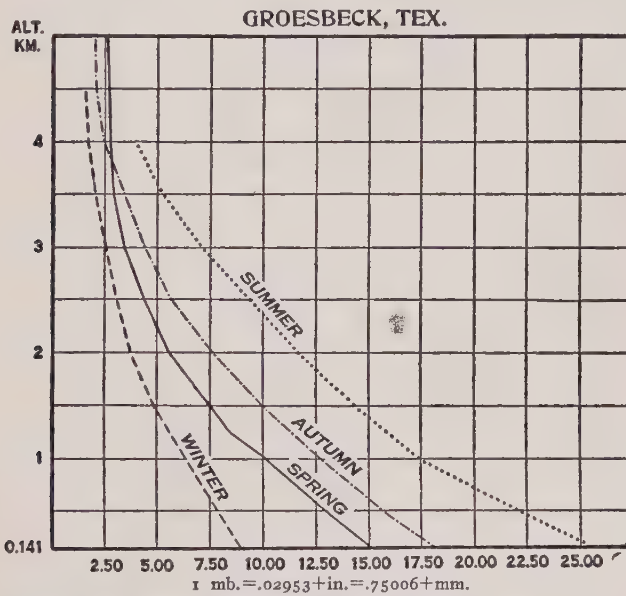


Figure 10. Mean Seasonal Free-air Vapor Pressures, mb., at Groesbeck, Texas

northern states. These characteristics of the vertical changes are shown in Figures 9 and 10.

Pressure. The pressure at any altitude is, in large part, a function of the surface pressure, the mean temperature of the air column and the water vapor. Other factors, such as variation of gravity with latitude and altitude, are not ordinarily considered, except in very precise altitude determination. The

usual statement of the pressure-altitude relation, disregarding unimportant factors, is

$$\log P = \log P_o - \frac{Z}{K\left(1 + \alpha\theta + .378\,\frac{e}{P}\right)}$$

in which:

P the pressure to be determined[1]

P_o that at some lower station

Z the difference in altitude between the two stations

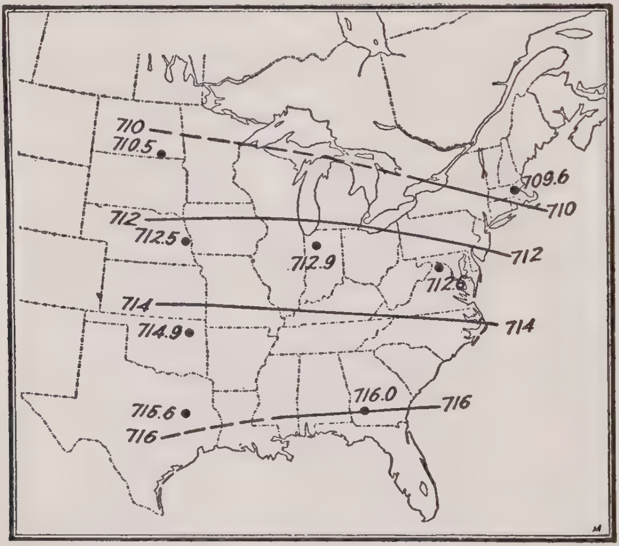
K the barometric constant

α the coefficient of expansion of air

θ the mean temperature of the air column

and

$\frac{e}{P}$ the ratio of the partial pressure of the water vapor to the total pressure

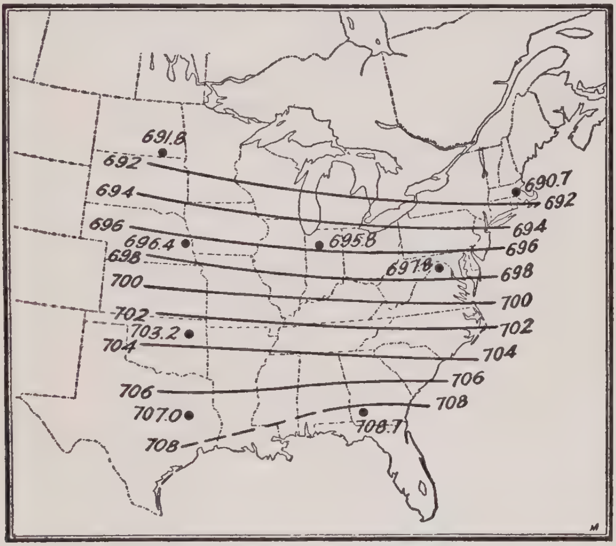


1 mb.=.02953+in.=.75006+mm.

Figure 11. Average Summer Pressures, mb., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

[1] This is, in shortened form, the well-known Laplacian hypsometric equation. Full discussions of its derivation and use may be found in numerous publications, some of the more recent being: "Physics of the Air," by W. J. Humphreys; "The Determination of the Altitude of Aircraft," by W. G. Brombacher, published in *Journal of the Optical Society of America and Review of Scientific Instruments*, Vol. 7, No. 9, pp. 719-774, September, 1923; "Smithsonian Meteorological Tables," 4th revised edition, 1918, pp. xxxix—*et seq.*

In this equation K and α are constants, (18,400 meters and .00367 for 1°C., respectively) $.378\ e/P$ is ordinarily small, and for a given altitude Z is, of course, a constant. Therefore, P varies principally with changes in P_0 and θ. When Z is small, P_0 is the more important; when it is large, i.e., as the altitude increases, θ exercises the larger effect. On the average then, at ordinary flying levels there is a pressure gradient from the tropics poleward. It is much more pronounced in winter than in summer, owing to the greater latitudinal contrast in tempera-



1 mb.=.02953+in.=.75006+mm.

Figure 12. Average Winter Pressures, mb., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

ture in the former season; in this season also the free-air pressures themselves at all latitudes are much lower than in summer. At sea level, as stated earlier, the annual variation consists of higher pressure over continents in winter than in summer with a corresponding decrease over the oceans. The difference between summer and winter pressures at 3 kilometers is

shown in Figures 11 and 12. The intimate relation between free-air pressures and temperatures is brought out by a comparison of these figures with Figures 7 and 8.

Density.[2] Atmospheric density varies directly with the pressure of the air and inversely with the temperature and moisture content. Expressed mathematically:

$$\rho = \rho_0 \frac{P - 0.378e}{P_0} \times \frac{T_0}{T}$$

in which

ρ is the density to be determined
ρ_0 is the density of dry air at pressure P_0 and temperature T_0
P and T are the given pressure and temperature respectively, and
e is the vapor pressure.

In simplified form this becomes

$$\rho = .46446 \times \frac{P - 0.378e}{273 + t}$$

in which ρ is expressed in Kg/m^3,
P and e in millimeters,
and t in degrees centigrade;

Or,

$$\rho = .34836 \times \frac{P - 0.378e}{273 + t}$$

in which P and e are expressed in millibars;

Or,

$$\rho = 1.3245 \times \frac{P - 0.378e}{459 + t}$$

in which ρ is expressed in lbs./ft.^{3},
P and e in inches,
and t in degrees Fahrenheit.

The annual range in density at the surface is on the average about 10%. The range from day to day is occasionally as large

[2] Specific weight. See footnote under "Units and Abbreviations," p. 5.

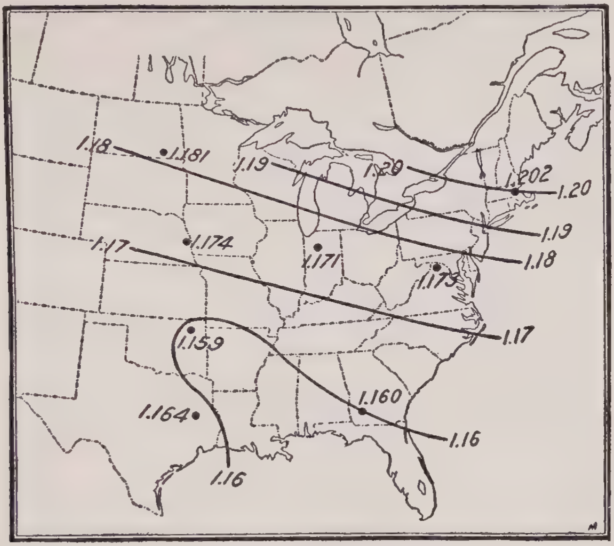


Figure 13. Average Summer Densities, kg./m³., in the United States East of the Rocky Mountains at Sea Level

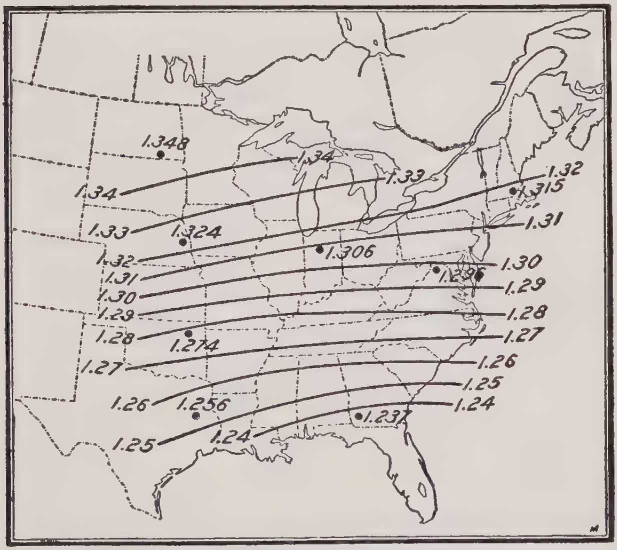


Figure 14. Average Winter Densities, kg./m³., in the United States East of the Rocky Mountains at Sea Level

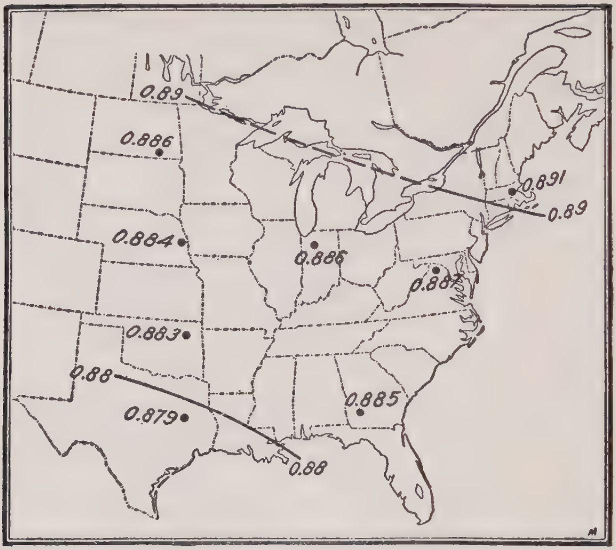


Figure 15. Average Summer Densities, kg./m³., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

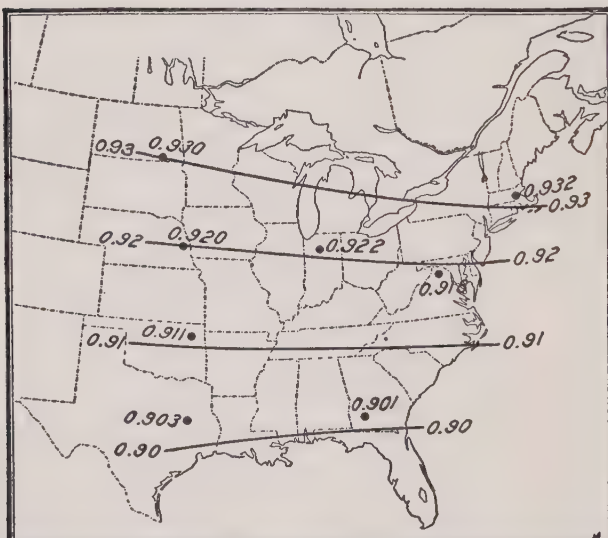


Figure 16. Average Winter Densities, kg./m³., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

as this, owing to changes in pressure and temperature, and the extreme range for the entire year may be 20% or more. It is higher in the temperate than in the torrid or arctic zones, higher at lowland than at mountain stations and much higher over the land than over the oceans. Figures 13 and 14 show the summer and winter means at sea level for the eastern part of the United States. The relation to temperature is well brought out by reference to Figures 1 and 2.

The range is much less above the earth's surface because, as previously stated, higher pressures accompany and in fact, are the result of higher temperatures at those altitudes and the two offset each other in their effect upon densities. Figures 15 and 16 show the small range at 3 kilometers. There is a further decrease with height until at about 8 kilometers density is constant throughout the year and in all parts of the world. Above this level it is higher in summer than in winter and in low latitudes than in high.

Average conditions at latitude 40° in the United States. At the request of the National Advisory Committee for Aeronautics a report was prepared in 1922 for the purpose of determining how closely the average conditions in the United States are in agreement with those proposed by Toussaint for general adoption as a "standard atmosphere." [3] In this study use was made of all available data obtained by means of kites and balloons at several stations near latitude 40°, this being approximately midway between the northern and southern limits of the country. These values were found to be sufficiently in accord with Toussaint's "standard atmosphere" to justify the National Advisory Committee for Aeronautics in adopting the latter, with slight modifications, for use in the United States.

In Table 2 are presented the results of this study. The characteristic differences between summer and winter, already

[3] Gregg, W. R., "Standard Atmosphere," National Advisory Committee for Aeronautics, Report No. 147, 1922.

TABLE 2.—MEAN-AIR BAROMETRIC AND VAPOR PRESSURES, TEMPERATURES AND DENSITIES AT ABOUT LATITUDE 40° IN THE UNITED STATES

Altitude, mean Sea Level	Pressure	Temperature	Vapor pressure	Density—Kilograms per Cubic Meter	Altitude, mean Sea Level	Pressure	Temperature	Vapor pressure	Density—Kilograms per Cubic Meter	Altitude, mean Sea Level	Pressure	Temperature	Vapor pressure	Density—Kilograms per Cubic Meter
SUMMER					WINTER					ANNUAL *				
m.	mb.	° C.	mb.		m.	mb.	° C.	mb.		m.	mb.	° C.	mb.	
0	1,014.0	25.0	22.0	1.175	0	1,020.0	−2.0	4.5	1.309	0	1,017.0	11.5	11.5	1.240
500	957.5	22.0	17.5	1.123	500	957.5	−3.0	3.5	1.234	500	957.5	9.5	9.5	1.176
1,000	904.0	19.0	14.0	1.072	1,000	899.0	−3.0	3.0	1.159	1,000	901.5	8.0	7.5	1.114
1,500	852.5	16.0	11.0	1.023	1,500	844.0	−4.0	2.5	1.092	1,500	848.5	6.0	6.0	1.056
2,000	803.5	13.0	8.5	0.975	2,000	792.0	−5.0	2.0	1.029	2,000	798.0	4.0	5.0	1.001
2,500	757.0	10.0	6.5	.929	2,500	743.0	−7.0	2.0	0.972	2,500	750.5	1.5	4.0	0.951
3,000	713.0	7.0	5.0	.885	3,000	697.0	−9.0	1.5	.918	3,000	705.0	−1.0	3.0	.902
4,000	630.5	0.5	3.5	.801	4,000	611.5	−14.5	1.0	.823	4,000	621.0	−7.0	2.0	.813
5,000	556.0	−5.5	2.0	.723	5,000	535.0	−20.5	0.5	.738	5,000	546.0	−13.0	1.0	.731
6,000	488.5	−12.5	1.0	.653	6,000	466.5	−27.5	....	.662	6,000	478.0	−20.0	0.5	.657
7,000	428.0	−19.5	0.5	.587	7,000	405.5	−34.5	....	.592	7,000	417.0	−27.0	....	.591
8,000	373.5	−26.0	....	.527	8,000	350.5	−41.0	....	.526	8,000	362.0	−33.5	....	.527
9,000	324.5	−32.5	....	.470	9,000	302.0	−46.5	....	.464	9,000	313.5	−39.5	....	.468
10,000	281.0	−39.0	....	.418	10,000	259.5	−50.0	....	.405	10,000	270.5	−44.5	....	.412
11,000	242.5	−45.5	....	.371	11,000	222.5	−52.5	....	.352	11,000	232.5	−49.0	....	.362
12,000	208.5	−52.0	....	.329	12,000	190.5	−54.0	....	.303	12,000	199.5	−53.0	....	.316
13,000	178.5	−55.0	....	.285	13,000	163.0	−55.0	....	.260	13,000	171.0	−55.0	....	.273
14,000	152.5	−55.0	....	.244	14,000	139.5	−55.0	....	.223	14,000	146.0	−55.0	....	.233
15,000	130.5	−55.0	....	.209	15,000	119.0	−55.0	....	.190	15,000	125.0	−55.0	....	.200
16,000	111.5	−55.0	....	.178	16,000	102.0	−55.0	....	.163	16,000	107.0	−55.0	....	.171
17,000	95.5	−55.0	....	.153	17,000	87.0	−55.0	....	.139	17,000	91.5	−55.0	....	.146
18,000	81.5	−55.0	....	.130	18,000	74.5	−55.0	....	.119	18,000	78.0	−55.0	....	.125
19,000	69.5	−55.0	....	.111	19,000	64.0	−55.0	....	.102	19,000	67.0	−55.0	....	.107
20,000	59.5	−55.0	....	.095	20,000	54.5	−55.0	....	.087	20,000	57.0	−55.0	....	.091

* The annual means also represent quite closely the average spring and autumn conditions.

discussed, are well shown, viz., the free-air pressures, except near the surface, the temperature lapse rates and the vapor pressures are higher in summer than in winter; density is essentially constant throughout the year at about 8 kilometers, but is higher in winter below that level and higher in summer above.

CHAPTER IV

WINDS

Although winds form an integral part of the vertical structure of the atmosphere, they are here treated in a separate section, because of their outstanding importance in aeronautics.

Direction. Owing to the earth's rotation, as already explained, air tends to flow at right angles to the pressure gradient or parallel to the isobars. At and near the surface, however, this tendency is not completely realized, because of friction and viscosity, with the result that air movement makes an angle with the isobars amounting on the average to 20° or 30°. It is much less than this, about 10°, at sea and greatest, sometimes 40° to 50°, in regions much broken up by hills, trees, buildings, etc.

Above the surface the influence of these obstructions rapidly diminishes and the wind direction is on the average very nearly parallel to the isobars at an altitude of about 500 meters. At greater heights, owing to the influence of temperature distribution, both vertical and horizontal, the pressure gradients differ widely from those at and near the surface, and the wind direction changes in conformity therewith. It is important to recognize that free-air winds are essentially parallel to the isobars[1] *at their own level* and that, in so far as they depart from surface gradient winds, they indicate a pressure distribution that is different from that at the surface.

Turning with altitude. A study of observations with kites and balloons shows that near the surface the turning of the winds is generally to the right, clockwise, no matter what the surface direction may be. This turning is most pronounced

[1] According to definition an **Isobar** is a line joining points at which the barometric pressure is the same either on the average for a stated period or at a specified moment.

with southerly surface winds, i.e., east through south to west-southwest, until at 3 to 4 kilometers it amounts on the average to somewhat more than 90°. With northerly winds, on the other hand, i.e., west-northwest through north to northeast or east-northeast, the turning is to the right but small in amount up to about 1 kilometer, and then changes to the left, counter-clockwise, at higher levels. The deviation is greater in winter than in summer at all stations and is also greater at northern than at southern stations. In other words, the turning is most pronounced when and where the latitudinal temperature gradient is strongest and hence the prevailing westerlies best developed. It is to be noted that in general the amount of the deviation in the upper levels varies directly, or nearly so, as the angle between the surface direction and a westerly direction. For example, a surface southeasterly wind turns more than does a surface southerly wind, both becoming as a rule south-westerly or west-southwesterly in the upper levels. Table 3

TABLE 3.—AVERAGE ANNUAL DEVIATION, DEGREES, OF FREE-AIR WINDS FROM SURFACE DIRECTION IN THE UNITED STATES EAST OF THE ROCKY MOUNTAINS

(Plus sign indicates turning to right; minus sign to left)

Surface Direction	Altitude, Meters					
	250	500	1,000	2,000	4,000	6,000
N	+ 5	+ 4	− 7	− 32	− 51	− 59
NNE	+ 10	+ 14	− 3	− 40	− 76	− 77
NE	+ 9	+ 13	+ 6	− 60	− 97	− 102
ENE	+ 10	+ 15	+ 22	− 56	− 118	− 125
E	+ 15	+ 25	+ 52	+ 146	+ 196	+ 210
ESE	+ 12	+ 26	+ 46	+ 88	+ 135	+ 160
SE	+ 19	+ 31	+ 51	+ 79	+ 116	+ 110
SSE	+ 12	+ 22	+ 37	+ 59	+ 102	+ 110
S	+ 13	+ 22	+ 36	+ 60	+ 77	+ 95
SSW	+ 11	+ 19	+ 34	+ 48	+ 66	+ 76
SW	+ 10	+ 17	+ 31	+ 40	+ 56	+ 68
WSW	+ 6	+ 13	+ 20	+ 25	+ 34	+ 56
W	+ 8	+ 11	+ 17	+ 19	+ 32	+ 37
WNW	+ 7	+ 10	+ 9	+ 4	+ 4	+ 17
NW	+ 4	+ 4	+ 1	− 8	− 3	− 13
NNW	− 1	+ 2	− 6	− 18	− 31	− 31

gives the average annual turning, in degrees, for the eastern and central United States according to surface wind direction.

The characteristic turning of different surface winds is well brought out also in Figure 17.[2]

The percentage frequencies of clockwise and counterclockwise turning are given in Table 4. They show that the tendency to clockwise turning is greater than that to counter-

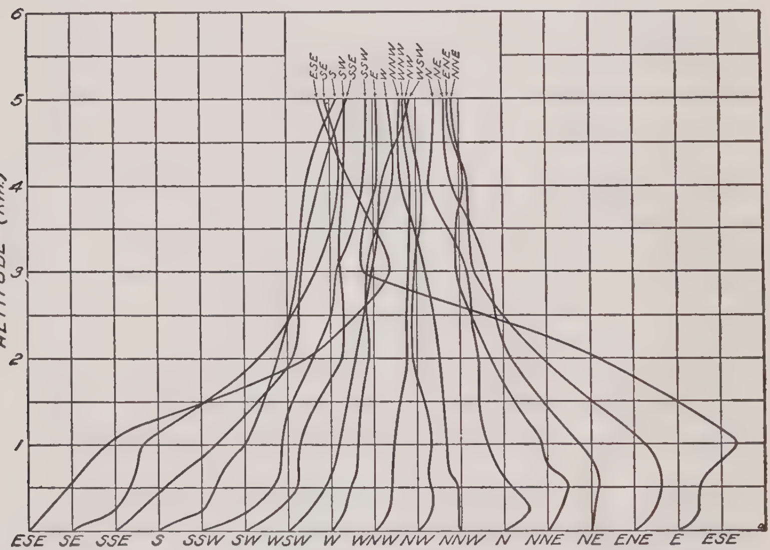


Figure 17. Average Turning of Surface Winds with altitude above Lansing, Mich. (after Ray)

clockwise for all directions near the surface but is most pronounced for southerly winds, i.e., east through south to west-southwest; this tendency increases with altitude for these southerly winds and amounts to 80 to 90 per cent at 3 to 4 kilometers; with northerly winds the tendency to clockwise turning does not change much with altitude, but the tendency to counterclockwise turning, small near the surface, increases to 60 to 80 per cent at 3 to 4 kilometers; the turning is more

[2] Ray, C. L., "Average Free-air Winds at Lansing, Mich.," *Monthly Weather Review,* Vol. 50, pp. 642-645, December, 1922.

pronounced, especially near the surface, in winter than in summer and at northern than at southern stations.

TABLE 4.—AVERAGE ANNUAL PERCENTAGE FREQUENCY OF CLOCKWISE (CW.) AND COUNTERCLOCKWISE (CCW.) TURNING OF WINDS FROM SURFACE DIRECTION IN THE UNITED STATES EAST OF THE ROCKY MOUNTAINS

Surface Direction	Altitude, Meters											
	250		500		1,000		2,000		4,000		6,000	
	cw.	ccw.	cw.	ccw.	cw.	ccw.	cw.	ccw.	cw.	ccw.	cw.	ccw.
N	38	25	41	30	34	44	24	62	20	73	18	64
NNE	46	18	49	23	41	41	30	61	22	73	25	71
NE	44	24	51	27	49	37	37	54	31	64	28	68
ENE	44	21	54	24	53	34	46	45	40	55	23	70
E	47	20	56	22	59	29	55	37	54	42	47	51
ESE	49	15	62	16	69	17	70	22	71	25	71	27
SE	56	14	66	15	75	16	74	19	75	22	73	25
SSE	51	13	66	13	74	14	80	16	84	12	79	21
S	47	13	60	12	75	11	84	10	88	9	85	13
SSW	42	14	56	14	71	11	80	9	86	8	86	10
SW	43	21	55	19	67	14	79	12	83	11	86	10
WSW	40	17	51	17	63	17	69	15	76	16	76	20
W	40	18	50	20	58	20	60	17	63	19	74	10
WNW	34	16	42	19	48	23	42	34	38	40	46	25
NW	36	21	40	26	38	29	32	45	30	51	23	56
NNW	31	21	36	27	34	41	21	60	17	73	20	68
Means	41	17	51	19	56	22	55	29	53	36	52	39

The shifting of winds with altitude into a westerly quarter is well shown in Figure 18. The more striking features of this figure are: (1) The greater percentage of easterly winds in summer than in winter (this is true at all levels); (2) the pronounced south component in summer, especially at southern stations, and the equally pronounced north component in winter, especially at northern stations; (3) the resulting predominance of a south component at southern stations and of a north component at northern stations for the year; and (4) the very large west components at all stations for the year in the upper levels.

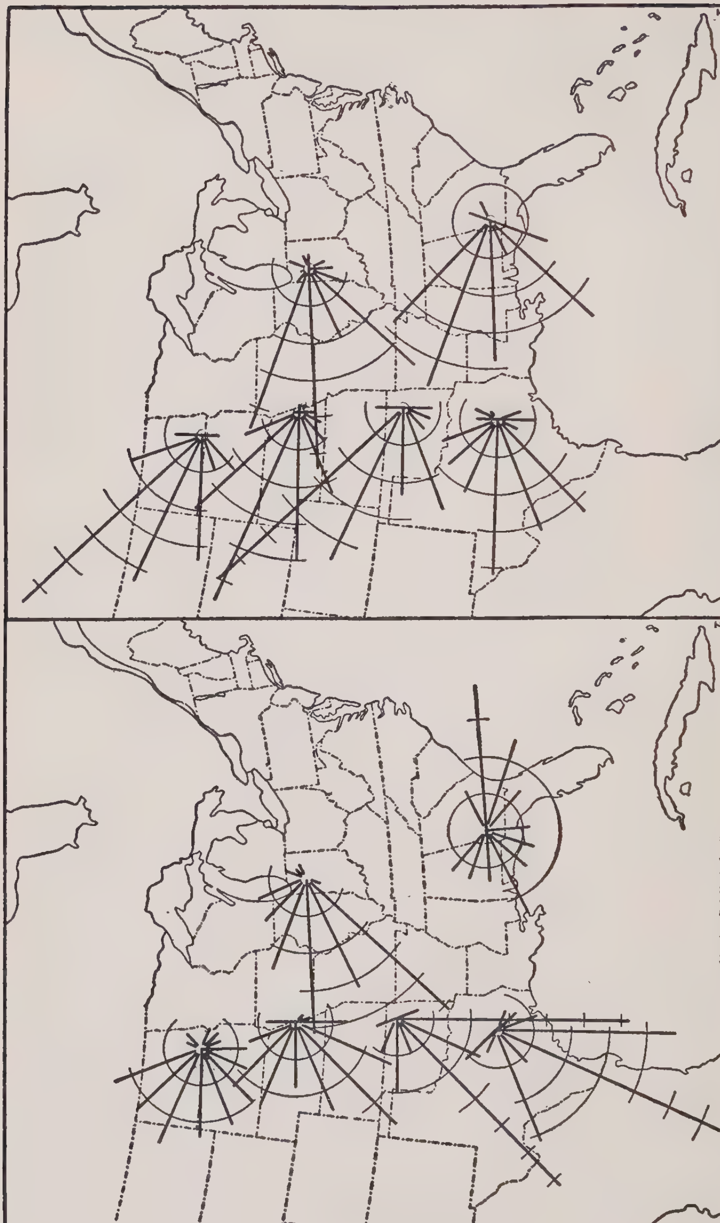


Figure 18. Percentage Frequency of Winds from Different Directions at 3 Kilometers above Sea Level

Velocity. Surface friction not only causes the winds to blow across the isobars, but also cuts down their speed to about half that indicated by the pressure gradient. On the average the gradient velocity is attained at an altitude of about 500 meters above the surface. If the pressure gradient is well defined, the corresponding wind speed, that at about 500 meters, can be computed with fair accuracy from well-known equations. These equations all involve the same terms, but differ slightly according to the type of pressure distribution prevailing, i.e., anticyclonic (isobars concentric around high pressure), cyclonic (isobars concentric around low pressure) or straight isobars.

The appropriate equations for these three types are respectively:

$$V = r\,\omega\sin\phi - \sqrt{(r\,\omega\sin\phi)^2 - r\,dP/\rho\,dn}$$

$$V = \sqrt{r\,dP/\rho\,dn + (r\,\omega\sin\phi)^2} - r\,\omega\sin\phi$$

and $V = (dP/dn)/2\,\omega\,\rho\sin\phi$,

in which V is the velocity in centimeters per second
r, the radius of curvature of wind path at place of observation, in centimeters
dP/dn, difference in dynes pressure per square centimeter, per centimeter horizontal distance at right angles to isobar
ω, angle through which the earth turns per second $= \dfrac{2\pi}{86{,}164}$
ρ, density of the air in grams per cubic centimeter
and $\sin\phi$, the natural sine of the angle of latitude

In "Physics of the Air," Dr. W. J. Humphreys has given tables for readily obtaining the gradient velocity for various conditions of pressure distribution.

When the pressure gradient is not known, velocities up to 400 or 500 meters above the surface can be determined approximately from the formula

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{1/5}$$

TABLE 5.—AVERAGE INCREASE, M.P.S., OF FREE-AIR WIND VELOCITIES ABOVE SURFACE VELOCITY IN U. S. EAST OF THE ROCKY MTS.

(The average velocities at different heights may be found by simply adding to the values given in columns 3 to 8 the average surface velocities in column 2.)

Surface		Altitude, Meters					
Direction	Veloc.	250	500	1,000	2,000	4,000	6,000
		SUMMER					
N	3.9	1.9	2.3	2.7	3.8	6.3	9.7
NNE	4.0	2.3	2.4	2.6	2.8	5.9	8.9
NE	3.7	2.0	2.6	2.5	2.7	4.8	7.9
ENE	4.0	2.3	2.6	2.7	2.5	4.4	6.1
E	3.8	1.8	2.2	2.8	2.9	3.6	4.9
ESE	3.9	2.1	2.2	2.0	1.9	2.7	5.1
SE	3.8	2.4	3.1	2.7	2.6	4.2	6.2
SSE	3.9	2.8	3.5	3.1	3.7	3.0	5.9
S	4.2	3.1	4.1	3.7	3.8	5.1	7.1
SSW	4.2	3.2	4.2	3.6	3.5	5.9	6.8
SW	4.1	3.4	3.9	3.7	3.7	5.6	7.2
WSW	3.5	3.3	4.2	3.9	4.6	6.6	11.2
W	3.6	3.1	3.8	4.0	5.3	7.8	8.8
WNW	3.8	3.5	4.4	4.6	5.2	9.0	10.9
NW	3.5	2.5	3.1	3.2	5.6	8.6	13.9
NNW	3.9	2.2	2.8	2.8	4.7	7.0	12.1
Calm	0.0	4.0	5.3	5.6	5.8	8.1	9.2
		WINTER					
N	4.8	2.9	3.7	4.6	7.1	14.0	18.7
NNE	4.6	2.8	3.4	3.4	5.0	10.2	17.8
NE	4.3	3.1	3.7	3.6	5.5	11.0	15.7
ENE	4.0	3.0	3.2	3.2	5.1	9.4	....
E	3.7	3.2	4.1	4.3	6.1	12.2	16.0
ESE	4.0	3.4	4.8	5.9	6.8	7.9	12.9
SE	4.0	3.6	5.2	6.1	8.0	12.2	....
SSE	4.8	4.5	6.4	7.5	9.8	13.1	....
S	5.0	4.3	6.2	7.5	9.6	15.1	....
SSW	4.9	4.6	6.6	8.9	10.9	14.1	....
SW	4.9	4.5	6.4	8.7	11.7	17.1	19.0
WSW	4.7	4.0	6.8	7.6	11.4	19.0	....
W	5.5	4.0	5.7	7.7	11.4	18.3	23.3
WNW	5.2	3.5	5.3	7.0	11.3	18.9	....
NW	5.8	3.5	4.7	6.7	10.6	17.9	23.7
NNW	5.5	3.2	4.2	6.2	9.5	17.7	....
Calm	0.0	4.9	7.1	8.8	11.9	18.0	23.0
		ANNUAL					
N	4.8	2.7	3.4	3.7	5.4	9.9	13.8
NNE	4.3	2.7	3.2	3.1	4.3	8.1	11.9
NE	4.1	2.8	3.4	3.2	4.1	8.0	11.7
ENE	4.0	2.8	3.0	2.9	3.4	7.0	11.0
E	3.9	2.5	3.2	3.4	4.1	7.2	10.7
ESE	3.9	2.9	3.6	3.6	4.2	7.6	11.4
SE	4.1	3.2	4.2	4.4	5.1	7.8	11.6
SSE	4.6	3.6	4.6	4.9	5.8	9.0	12.2
S	4.9	3.9	5.5	5.7	6.4	9.5	12.5
SSW	4.8	4.0	5.2	6.0	6.9	9.6	11.9
SW	4.6	3.8	4.9	5.7	7.3	10.6	13.2
WSW	4.5	3.6	4.7	5.3	7.8	11.9	13.2
W	4.6	3.5	4.5	5.5	8.2	12.6	17.4
WNW	4.9	3.4	4.4	5.5	8.4	13.8	19.1
NW	5.0	3.1	4.0	5.0	7.8	13.3	17.6
NNW	5.0	2.9	3.6	4.5	7.0	12.1	16.3
Calm	0.0	4.5	6.0	6.7	8.3	12.8	16.2

in which h is the height in meters above the surface for which the velocity V in meters per second is to be computed, and h_0 the known height (not less than 16 meters) at which the velocity V_o is measured.[3]

The average change of velocity with altitude for different surface directions in the eastern and central United States is shown in Table 5. The figures given indicate that in the lower levels up to an altitude of about 1 kilometer the largest increases in velocity occur above surface southeasterly to southwesterly winds, but at greater heights, i.e., 1½ to 4 kilometers (and presumably thence up to the base of the stratosphere) the largest increases are found above surface southwesterly to northwesterly winds. They are least in all seasons and at all heights above surface northeasterly to east-southeasterly winds.

Annual variation. Figure 19 shows the characteristic seasonal change in free-air speeds in Oklahoma and East Texas.[4] Similar charts for northern stations would show the same features with, however, somewhat higher velocities in summer.

Diurnal variation. As is well known, wind velocity at the surface is higher during the day than at night. The maximum occurs on the average between noon and 3 P. M. and the minimum between midnight and 6 A. M. It is not so well known, but should be clearly recognized, that the daily march at upper levels is the exact opposite of this, as shown in Figure 20.[5] It is to be noted that the variation characteristic of the surface extends only to about 100 meters, and that it amounts on the average to only about 2 m. p. s., whereas that at higher levels is 3 or 4 m. p. s. It is largest between 400 and 600 meters above the surface.

Average directions and velocities. Average seasonal values at Drexel, Neb. (near the central part of the country)

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[3] Hellman, J. G. "Sitz. der K. Preuss. Akad. der Wiss.," p. 191, 1917.
[4] Riley, J. A., *Monthly Weather Review*, Vol. 51, pp. 448-455, September, 1923.
[5] Riley, loc. cit., p. 453.

are shown in Figure 21. The more prominent features are: the large increase in velocity in the first 500 meters above the surface; a more gradual increase at greater heights (in summer and frequently in the other seasons also, there is an actual decrease from about 500 to 1,000 meters above the surface, most pronounced at southern stations); the decided seasonal variation in the upper levels; the seasonal lag, i.e., higher velocities in spring than in autumn; and the close approach to a westerly direction in the higher levels, this feature being most in evidence at the northern stations. Above the influence of convec-

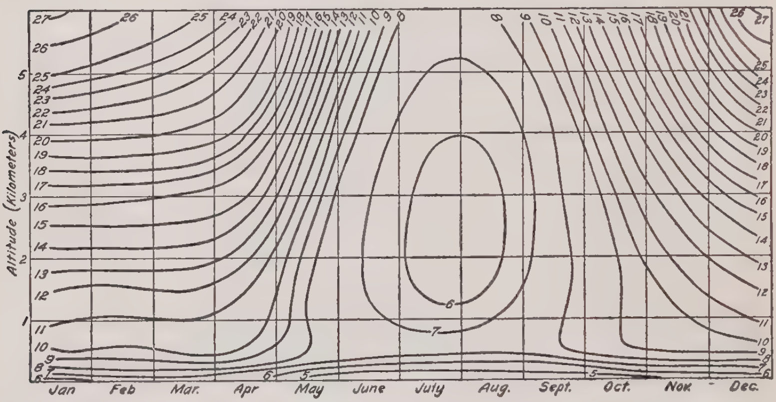

Figure 19. Average Free-air Wind Velocities, m. p. s., for all Directions in Oklahoma and East Texas (after Riley)

tion, i.e., 2,000 to 3,000 meters, the velocity increases on the average inversely as the density of the air decreases.[6]

Gustiness. The principal sources of gustiness are local heating, topographic irregularities and buildings. Local heating is more pronounced over a black soil than over a light one; over a ploughed field than over a pasture and over land in general than over water. The resulting changes in air density give rise to vigorous convection which produces a bodily uplift or drop of the aircraft, with changes in the

[6] Egnell's Law, first stated, however, by H. H. Clayton.

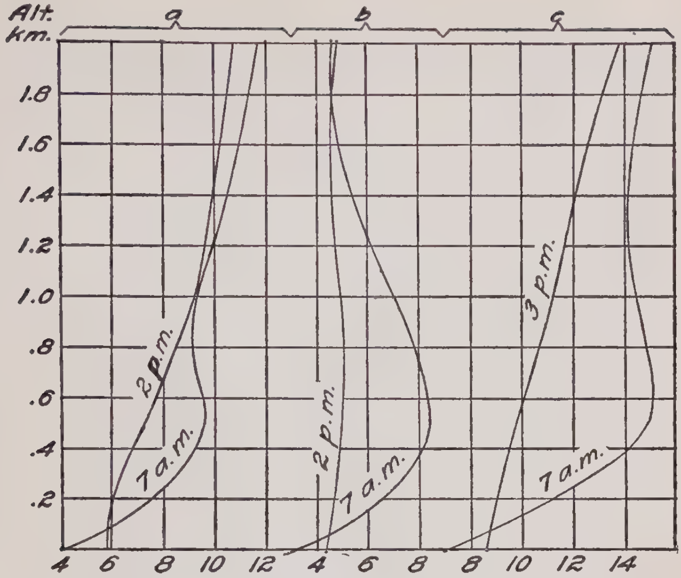

Figure 20. Average A.M. and P.M. Velocity Curves

(a) January, and (b) July, at Groesbeck, Texas; (c) March at Broken Arrow, Okla. (after Riley).

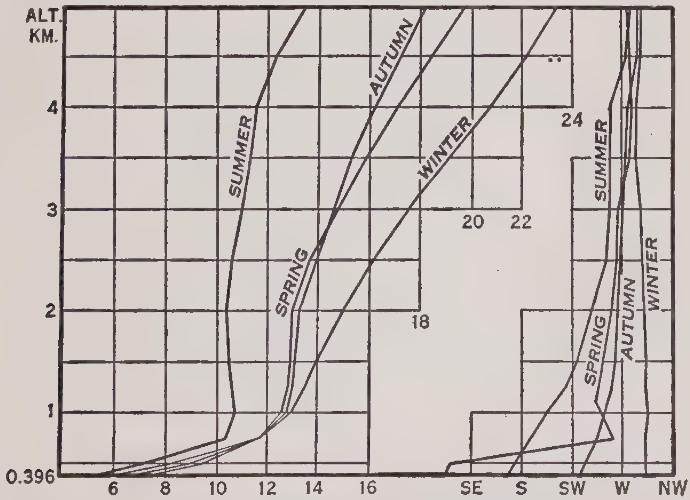

Figure 21. Average Seasonal Free-air Wind Directions and Velocities, m. p. s., at Drexel, Neb.

angle of attack as the column of ascending or descending air is entered or left. If, as sometimes happens, only a portion of the aircraft is affected by such a column, e.g., one wing is in rising air and the other is not, a decided tilting of the machine is produced. The chief danger, except near the surface, is the tendency to overadjust the machine in going from one condition into another. If, for instance, on entering a column of rising air, the angle of attack is so changed as to keep the machine at a constant level, an abrupt drop (popularly known as "air pocket" or "hole in the air") will occur as the column of rising air is left. Caution is necessary in such cases, especially when flying comparatively near the surface.

Convection is most active on summer afternoons, particularly in the vicinity of cumulus clouds. Many cases are on record in which vertical movements of 3 to 4 m. p. s. have been observed.

J. A. Riley [7] reports an observation with a pilot balloon, showing an ascending air movement of 4.4 m. p. s. from the surface to an altitude of about 1 kilometer. This observation was made directly underneath a large cumulus cloud. Dr. C. F. Brooks [8] observed an upward movement of 7 m. p. s. at Blue Hill, Mass. Such very high velocities are rare, however, except in thunderstorms. In the latter they amount to 8 or 10 m. p. s., doubtless more in many cases.

Buildings and topographic irregularities produce eddies and gusts, their influence extending to a considerable height, on the average about four times that of the obstructions themselves above the general level of the earth's surface in their vicinity. In addition there is the danger from turbulence in the lee of obstructions. Major Blair has cited a case of this kind.[9] The obstruction was a small circular building, kite reel shelter, about 18 feet in diameter and 20 feet high, set

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[7] "Flying Weather in the Southern Plains States," *Monthly Weather Review*, Vol. 47, pp. 631-632, November, 1920.

[8] "Scarf Clouds," *Monthly Weather Review*, Vol. 45, p. 363, July, 1917.

[9] Blair, W. R., "Meteorology and Aeronautics," Report No. 13, National Advisory Committee for Aeronautics, 1917.

Mount Weather, Va. Wm. R. Blair

Plate I.—Disturbance Caused to Leeward of a Small Round Tower During a High Wind

in a cleared space on which snow had recently fallen. (See Plate I.) A wind of about 50 m. p. h. was blowing. On the leeward side of this building "the ground was kept bare of snow for a width of about 10 feet and a distance of 525 feet; at this point the surface took a decided downward slope. As the air current passed the tower two helices were formed. To one standing in the tower the rotation of the air in the helix on his left was clockwise; on his right counterclockwise, as shown by the suspended snow. The air descending in the middle of the path swept the snow outward and forward to both sides."

The turbulence along a mountain ridge is not always a disadvantage as the following account shows:[10]

"As the country around Tucson was approached, it became a continuous struggle, with the climb at practically the absolute ceiling of the airplane, in order to cross over the high passes, mountains, and elevations, the passing of each obstacle being doubtful.

"The atmosphere was very rough and bumpy, with numerous air currents, which would raise the airplane 100 feet or more at a time, sometimes possibly 200 or 300, and then let it down quickly, even though the same position or angle of climb of the machine was maintained. Many times it seemed that the T-2 would not be able to get over these high areas, but, apparently just as the summit was reached, one of the air currents coming over the high elevation would raise the airplane just enough to clear the top." Apparently this process was assisted by a return eddy near the surface, blowing up the mountain on the lee side.

Fortunately the gustiness from all these causes rapidly diminishes with height and is as a rule not troublesome above 200 or 300 meters, though extending at times to a kilometer or more in very rough country during high winds. At and

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[10] Macready, Lieut. John A., "The Non-Stop Flight Across America," *National Geographic Magazine*, July, 1924, p. 33.

near the surface the fluctuations amount in extreme cases to slightly more than 50 per cent of the mean wind speed, i.e., if the latter is 20 m. p. s., the extremes are approximately 10 and 30 m. p. s. A condition such as this is exceedingly dangerous to aircraft. Going into the wind it would rise in the gust and fall in the lull; going with the wind, the opposite would be true.[11]

Winds at very high altitudes. Occasionally a report appears in the press or in one of the periodicals that an aviator flying at a great height had encountered a "trade wind from the west of 200 or 300 miles per hour." Such statements are utterly misleading. A "trade" wind implies a close approach to constancy of direction; and a velocity of 200 or 300 miles per hour, although it may sometimes occur, has never been actually observed under circumstances susceptible of verification. Certainly such speeds are of extremely rare occurrence. As for direction at these great heights, it is from some westerly point as a rule, but varies from north-northwest to south-southwest, being more frequently from northwest or southwest than from due west. Moreover, it is occasionally from an easterly point, quite frequently so in the extreme southern states during summer.

Wind factor in flight. In fixing regular flying schedules between two points it is essential to know: (a) the wind factor or resultant wind for which allowance must be made; and (b) the frequency of head or cross winds of different speeds along the course that will cut down the ground speed. There are two ways in which these values can be determined: (1) From actual free-air observations with kites and balloons or other means; and (2) from the records of a regular flying service that has been in operation for at least a year. Both of these methods have been employed in a study of conditions

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[11] Useful discussions of winds adverse to aviation are contained in W. J. Humphrey's "Physics of the Air," and in a paper by C. F. Brooks published in the *Monthly Weather Review*, August, 1919, entitled "Effect of Winds and Other Weather Conditions on the Flight of Airplanes."

between New York and Chicago and have been found to agree closely.[12] The results of this study show that at ordinary flying levels the wind factor is about 7.5 m. p. h. (3.5 m. p. s.). By "ordinary flying levels" is meant 1,000 to 5,000 ft. (300 to

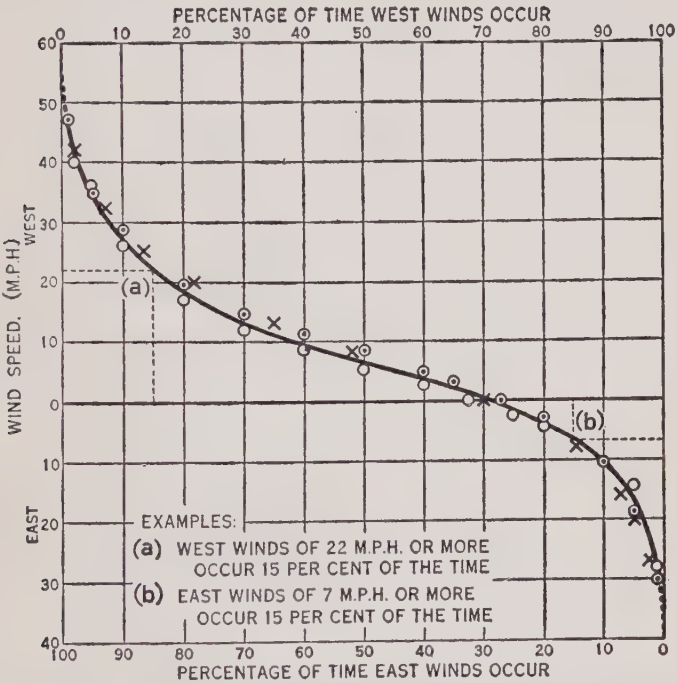

Figure 22. Annual Percentage Occurrence of East and West Component Winds of Different Speeds at Ordinary Flying Levels along the New York-Chicago Route

The crosses are based on kite and balloon observations; open circles on westbound Air Mail flights; and circles with a dot, on eastbound flights.

1,500 m.). The altitude of flight of the Air Mail planes varied according to the weather and wind conditions prevailing, but, fortunately for the purposes of this study, the wind velocity does not greatly change on the average within the

[12] Gregg, W. R., and Van Zandt, Lieut. J. P., "The Wind Factor in Flight: An Analysis of One Year's Record of the Air Mail," *Monthly Weather Review,* Vol. 51, pp. 111-125, March, 1924; and "The Frequency of Winds of Different Speeds at Flying Levels between New York and Chicago: A Further Analysis of the Records of the Air Mail Service," *Monthly Weather Review,* Vol. 52, pp. 153-157, March, 1924.

altitude limits above given, as indicated in Figure 21. The data from these flights and from kite and balloon observations also made possible the determination of the frequency of opposing winds of various speeds. There were included not only the head winds but also the equivalent component effect of cross winds. The frequencies thus determined are shown in Figure 22.

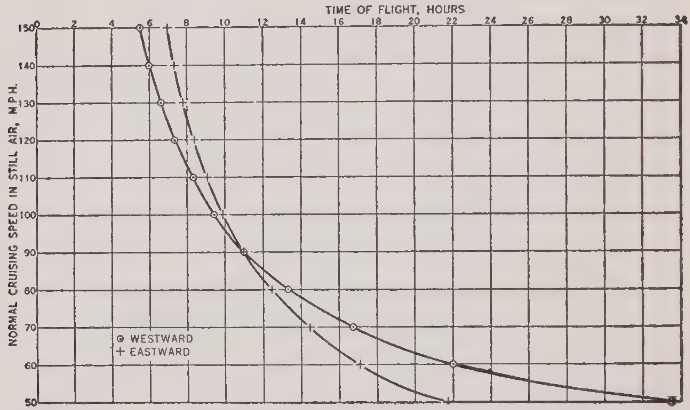

Figure 23. Curves Showing Schedules for Westward and Eastward Flight between New York and Chicago, 770 miles, that can be guaranteed 90% of the time for aircraft of different cruising speeds

Allowance made for unfavorable weather conditions; head and cross winds; 1 hour service stops each way and change in time.

With these frequencies it is possible to fix schedules for aircraft of different cruising speeds that can be guaranteed any desired percentage of the time so far as winds are concerned. Such schedules are given in Figure 23 on the basis of a 90 per cent guarantee, allowance being made for failures 5 per cent of the time on account of opposing winds and 5 per cent because of other unfavorable conditions, such as severe rain or snow storms, poor visibility, etc. Allowance is also made for 1 hour service stops each way and for the difference in time, i.e., the times shown are those by the clock in the two cities, not actual elapsed time.

The importance of the close agreement between the Air Mail records and the kite and balloon data lies in the fact that either can be used, when both are not available for other regions where regular flying service is to be established on a commercial basis.

TABLE 6.—AVERAGE ANNUAL PERCENTAGE FREQUENCY OF FREE-AIR WINDS OF DIFFERENT SPEEDS AT 500, 1,000, 2,000 AND 4,000 METERS, CLASSIFIED ACCORDING TO WIND DIRECTION, FOR MIDDLE LATITUDES IN THE UNITED STATES

Wind Direction	Wind Speed, m.p.s.											
	500 METERS						1,000 METERS					
	1–4	5–9	10–14	15–19	20–29	30+	1–4	5–9	10–14	15–19	20–29	30+
N	1.9	2.2	0.9	0*	0	0	1.3	2.2	1.2	0.2	0.1	0
NNE	1.8	1.7	0.3	0*	0	0	1.3	1.8	0.6	0.1	0	0
NE	1.4	1.9	0.4	0*	0	0	1.8	2.3	0.5	0.1	0	0
ENE	1.6	1.8	0.4	0*	0	0	1.6	1.4	0.2	0*	0	0
E	1.2	1.5	0.6	0.2	0*	0	1.1	1.4	0.2	0.1	0*	0
ESE	1.4	1.5	0.2	0.1	0	0	1.3	0.6	0.4	0.1	0*	0
SE	1.6	1.6	0.1	0.1	0	0	1.1	1.0	0.1	0*	0	0
SSE	1.6	1.7	0.6	0.1	0	0	1.5	1.4	0.4	0*	0	0
S	1.6	2.7	1.0	0.5	0.1	0	0.9	2.3	0.8	0.1	0*	0
SSW	1.8	3.2	2.4	0.8	0.4	0	1.5	2.6	1.4	0.7	0.5	0*
SW	2.0	3.9	3.2	1.4	0.3	0	1.8	3.7	3.6	1.6	0.6	0
WSW	1.7	4.0	3.2	1.7	0.4	0	1.6	3.7	3.6	1.8	0.7	0
W	2.0	5.3	3.9	1.3	0.1	0*	2.3	4.6	4.6	2.2	0.6	0*
WNW	2.0	3.4	2.1	0.4	0*	0	1.5	3.2	3.8	1.4	0.3	0
NW	1.6	3.2	1.3	0.2	0	0	1.5	3.9	1.9	0.6	0.4	0
NNW	1.6	3.1	1.0	0.2	0	0	1.5	2.9	1.3	0.2	0	0
	Calm 0.4						Calm 0.2					

Wind Direction	2,000 METERS						4,000 METERS					
	1–4	5–9	10–14	15–19	20–29	30+	1–4	5–9	10–14	15–19	20–29	30+
N	1.3	2.3	1.1	0.5	0	0	0.5	1.3	0.4	0.7	0	0
NNE	0.8	1.6	0.3	0.2	0	0	0.6	0.9	1.2	0.1	0.1	0
NE	1.1	1.3	0.3	0	0	0	0.3	0.7	0.3	0	0	0
ENE	0.4	0.5	0.1	0.1	0	0	0.9	0.4	0	0	0	0
E	0.9	1.0	0.2	0	0	0	0.4	0.6	0	0	0	0
ESE	0.6	0.5	0*	0	0	0	0.5	0.8	0	0	0	0
SE	0.4	0.7	0.2	0	0	0	0.7	0.1	0	0	0	0
SSE	1.3	1.0	0.4	0.3	0	0	0.3	0.5	0	0	0	0
S	0.9	1.2	0.6	0.1	0	0	1.0	1.5	0.6	0.3	0	0
SSW	0.9	2.1	1.8	0.6	0.1	0	0.4	2.0	0.9	0	0	0
SW	1.6	3.0	2.2	1.4	0.6	0	0.5	3.4	2.0	1.1	0.3	0
WSW	1.1	4.0	4.8	2.3	1.0	0	0.8	1.6	1.8	2.0	1.0	0.4
W	1.3	3.8	4.4	3.1	1.4	0.1	1.2	3.8	4.6	4.0	3.8	0.2
WNW	1.4	5.0	4.6	3.8	1.8	0.2	1.0	4.2	6.0	4.5	2.9	1.1
NW	1.6	3.4	3.4	2.4	0.9	0.1	1.8	5.2	6.2	4.4	2.8	0.4
NNW	1.1	3.4	1.5	1.0	0.4	0	1.8	2.0	2.3	1.2	0.4	0
	Calm 0.1						Calm 0.3					

* Less than 0.05 per cent.

Frequencies of different wind speeds at various levels, classified according to wind direction, and resultant wind

values have been determined for all portions of the United States east of the Rocky Mountains and can be obtained in detail from the U. S. Weather Bureau.[13] In general, westerly winds have the largest percentage frequency of the higher velocities, and this distribution becomes more pronounced as higher levels are reached. Table 6 gives the values that have been determined for middle latitudes in the United States, i.e., Nebraska and Kansas eastward to Pennsylvania and Virginia.

[13] Part II of "An Aerological Survey of the United States."

CHAPTER V

FOGS AND CLOUDS

Fogs

Formation. Fogs are formed in two ways: (1) by radiation, and (2) by mixture of adjacent masses of air having decidedly different temperatures. The first type is usually local in character, occurring at night during the summer half of the year in clear, quiet weather. River valleys and low lying marshy land are especially favorable for its formation, because of the large amount of water vapor that air in those regions usually contains and because of the cooling by radiation and air drainage. Fog of this type is of shallow depth as a rule and dissipates within an hour or so after sunrise under the influence of the strong surface heating and the resulting greater capacity of the air for moisture.

The second type, called "advection fog" by Humphreys, has much the greater importance, so far as the aeronaut is concerned. It is most frequently caused by the drifting of warm, humid, air over a cold surface, and is therefore of quite general occurrence along coast lines and the shores of large lakes at times of sharp contrast between temperatures over the land and water. Dense fogs occur also at sea, some distance from land, whenever there is a mixture of air overlying two adjacent regions of decidedly different temperatures. A conspicuous example is that of the fogs in the vicinity of Newfoundland, caused by the cooling of the humid Gulf Stream air as it blows over the Labrador Current.

Frequency. In the United States fog is most frequent along the northern and middle portion of the Atlantic and

Pacific coasts, especially in New England and near San Francisco Bay. The Pacific coast as a whole is foggier than the Atlantic owing to the difference in the prevailing winds, onshore, therefore humid, in the former case and offshore, therefore comparatively dry, in the latter. At Point Reyes Light, near San Francisco, dense fog on the average occurs on 137 days in the year. Along the south Atlantic and Gulf coasts the average number of days is from 10 to 20, except in southern Florida where fog is of very rare occurrence. In the Lake region the number ranges from about 20 along the upper Lakes to about 10 along the lower.

The seasonal distribution is in general: A maximum in the summer months along the Pacific and New England coasts and in the upper Lake region; and a maximum in the winter months along the south Atlantic and Gulf coasts; elsewhere no marked seasonal variation. Table 7 shows the average monthly and annual number of days with dense fog for selected stations. No interior points are given, as fogs there are infrequent, less than 10 a year as a rule, and moreover are generally of the radiation type and therefore of short duration.

Height of fog. Radiation fogs are almost invariably very shallow, rarely exceeding 100 meters in height. Advection (air mixture) fogs extend as a rule to a somewhat greater height, in some reported cases well above 1 kilometer, but on the average they probably range between 50 and 1,000 meters with the greater number within 500 meters. Precise data on this point are lacking, however.

Mountain fogs. These as a rule are simply low lying clouds covering the mountain tops and therefore frequently extend to a much greater height than ordinary fogs. Generally the valleys are clear and it is possible to evade the fog by flying low.

Artificial dissipation of fog. Owing to the great danger that attends landing in a fog, considerable thought has been

TABLE 7.—AVERAGE NUMBER OF DAYS WITH DENSE FOG AT SELECTED STATIONS IN THE UNITED STATES

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
ATLANTIC COAST													
Eastport, Me.	2	2	2	3	5	6	10	9	5	3	2	1	50
Portland, Me.	1	1	1	2	2	2	3	4	3	2	1	1	23
Nantucket, Mass.	4	3	6	5	8	8	10	8	6	3	2	2	65
New York, N. Y.	3	3	3	2	2	1	1	0	1	2	2	3	23
Philadelphia, Pa.	2	1	1	0	0	0	0	1	1	2	2	2	12
Atlantic City, N. J.	2	2	2	2	3	2	1	1	1	2	1	2	21
Washington, D. C.	2	1	1	1	0	0	0	0	1	2	2	2	12
Norfolk, Va.	1	2	1	0	1	0	0	0	0	2	1	2	10
Hatteras, N. C.	2	3	2	1	0	0	0	0	0	1	1	1	11
Wilmington, N. C.	2	1	1	0	0	0	0	0	1	2	1	2	12
Charleston, S. C.	4	3	3	0	1	0	0	0	1	2	2	3	19
Jacksonville, Fla.	3	1	1	0	0	0	0	0	0	1	1	2	9
GULF COAST													
Key West, Fla.	0	0	0	0	0	0	0	0	0	0	0	0	0
Tampa, Fla.	3	2	1	1	0	0	0	0	0	1	1	2	11
Pensacola, Fla.	3	3	3	1	0	0	0	0	0	0	1	2	13
New Orleans, La.	4	2	3	1	0	0	0	0	0	1	3	2	16
Galveston, Tex.	6	4	5	1	0	0	0	0	0	0	2	3	21
Corpus Christi, Tex.	2	2	2	0	0	0	0	0	0	1	1	2	10
PACIFIC COAST													
Tatoosh Isl'd, Wash.	1	1	1	1	3	4	8	11	8	5	1	1	45
Tacoma, Wash.	4	4	3	1	1	0	0	1	4	9	6	6	39
Eureka, Calif.	4	3	3	1	2	2	6	7	9	9	5	3	54
Point Reyes Light, Calif.	8	8	7	7	9	12	20	21	15	13	10	7	137
San Francisco, Calif.	2	2	1	1	1	1	2	2	2	2	3	2	21
Los Angeles, Calif.	1	2	2	2	2	3	4	3	4	3	2	1	29
San Diego, Calif.	2	2	1	2	0	1	1	1	2	4	3	1	19
GREAT LAKES													
Duluth, Minn.	1	0	1	2	3	3	2	2	2	1	1	1	19
Marquette, Mich.	0	0	1	1	3	3	2	2	1	1	0	0	14
Sault Ste. Marie, Mich.	2	2	2	1	1	1	1	2	3	3	1	1	20
Escanaba, Mich.	2	1	2	2	2	1	1	2	2	2	1	1	19
Milwaukee, Wis.	1	1	1	1	2	2	1	1	1	2	1	2	16
Chicago, Ill.	1	1	1	1	0	0	0	0	1	1	1	1	8
Grand Haven, Mich.	1	1	1	1	2	1	1	1	1	1	1	1	13
Port Huron, Mich.	1	1	1	1	1	1	0	1	2	2	1	1	13
Detroit, Mich.	2	1	1	1	0	0	0	0	1	2	1	2	11
Cleveland, Ohio	1	1	1	1	0	0	0	0	0	0	1	1	6
Buffalo, N. Y.	1	1	1	2	1	1	0	0	0	1	1	1	10

"0" indicates either none, or less than one in 2 years.

given to the possibility of devising means for keeping clear a small area in the vicinity of airdromes. Three methods have been proposed: (1) Sprinkling with electrified sand or spray; (2) drying or evaporating by heating; and (3) drainage through an underground tunnel. Each of these methods would prove effective and probably practicable if there were no movement of the air, i.e., if the problem were merely to clear a portion of air of the fog particles that it contains at any one time. But the air is nearly always in motion, and therefore a portion of it once cleared would be almost immediately replaced by another portion as bad as the first. Dr. W. J. Humphreys [1] has found that, to clear an airdrome, 500 meters square, of fog 50 meters deep moving at the very moderate rate of 100 meters per minute, would require, by the first method, more than a ton of sand per minute; by the second method, something like 6,600 gallons of oil or 35 tons of coal per hour; and by the third method, assuming suitable openings in the ground leading to an underground channel with an outlet some distance away, at least 110,000 horsepower to force the air through. Obviously all of these schemes are utterly impracticable, except possibly in cases of great emergency where the item of expense need not be considered.

Clouds

Formation. The process of cloud formation is the same as that of fogs, viz., condensation of the water vapor caused by cooling of the air below the dew point. Fog, however, is a surface phenomenon, and the cooling is induced as a rule by radiation or by the mixture of air of different temperatures. Clouds, on the other hand, are free-air phenomena, though at times their bases lie very close to the surface. Radiation is not in any large sense a factor in their formation, but mixing of air of different temperatures is one of the agencies

[1] In "Trying to Control Rain," Manuscript, to be published later.

producing clouds. The most important and frequent cause is the cooling brought about by vertical convection, either thermal as on a hot afternoon, or mechanical as over a mountain ridge or by the gradual forced ascent of air above an underrunning current of relatively denser air, and by turbulence.

Types. Clouds are not classified, like fogs, according to their causes, but rather according to their form or appearance. The cloud types adopted by the International Conference of Directors of Meteorological Institutes and Observatories at Innsbruck in 1905, and their definitions as published in the International Cloud Atlas, second edition (Paris, 1910), are as follows:

1. **Cirrus** (Ci.). *Detached clouds of delicate and fibrous appearance, often showing a featherlike structure, generally of a whitish color.* Cirrus clouds take the most varied shapes, such as isolated tufts, thin filaments on a blue sky, threads spreading out in the form of feathers, curved filaments ending in tufts, sometimes called *Cirrus uncinus,* etc.; they are sometimes arranged in parallel belts which cross a portion of the sky in a great circle, and by an effect of perspective appear to converge toward a point on the horizon, or, if sufficiently extended, toward the opposite point also. (Ci.-St. and Ci.-Cu., etc., are also sometimes arranged in similar bands.)

2. **Cirro-stratus** (Ci.-St.). *A thin, whitish sheet of clouds* sometimes covering the sky completely and giving it only a milky appearance (it is then called *Cirro-nebula*) at other times presenting, more or less distinctly, a formation like a tangled web. This sheet often produces halos around the sun and moon.

3. **Cirro-cumulus** (Ci.-Cu.), **Mackerel Sky.** *Small globular masses or white flakes without shadows, or showing very slight shadows, arranged in groups and often in lines.* [Small A.-Cu. may also be "Mackerel Sky."]

4. **Alto-stratus** (A.-St.). *A thick sheet of a gray or bluish color,* sometimes forming a compact mass of dark gray color and fibrous structure. At other times the sheet is thin, resembling thick Ci.-St., and through it the sun or the moon may be seen dimly gleaming as through ground glass. This form exhibits all changes peculiar to Ci.-St., but from measurements its average altitude is found to be

about one-half that of Ci.-St. [Nonfibrous A.-St. is often undulated or festooned.]

5. **Alto-cumulus** (A.-Cu). *Largish globular masses, white or grayish, partially shaded, arranged in groups or lines, and often so closely packed that their edges appear confused.* The detached masses are generally larger and more compact (resembling St.-Cu.) at the center of the group, but the thickness of the layer varies. At times the masses spread themselves out and assume the appearance of small waves or thin slightly curved plates. At the margin they form into finer flakes (resembling Ci.-Cu.) They often spread themselves out in lines in one or two directions.

6. **Strato-cumulus** (St.-Cu.). *Large globular masses or rolls of dark clouds often covering the whole sky, especially in winter.* Generally St.-Cu. presents the appearance of a gray layer irregularly broken up into masses of which the edge is often formed of smaller masses, often of wavy appearance resembling A.-Cu. Sometimes this cloud-form presents the characteristic appearance of great rolls arranged in parallel lines and pressed up against one another. In their centers these rolls are of a dark color. Blue sky may be seen through the intervening spaces, which are of a much lighter color. St.-Cu. clouds may be distinguished from Nb. by their globular or rolled appearance, and by the fact that they are not generally associated with rain.

7. **Cumulus** (Cu.), **Woolpack Clouds.** *Thick clouds of which the upper surface is domeshaped and exhibits protuberances while the base is horizontal.* These clouds appear to be formed by a diurnal ascensional movement which is almost always noticeable. When the cloud is opposite the sun, the surfaces facing the observer have a greater brilliance than the margins of the protuberances. When the light falls aslant, as is usually the case, these clouds throw deep shadows; when, on the contrary, the clouds are on the same side of the observer as the sun, they appear dark with bright edges.

True cumulus has well-defined upper and lower limits, but in strong winds a broken cloud resembling cumulus is often seen in which the detached portions undergo continual change. This form may be distinguished by the name *Fracto-cumulus* (Fr.-Cu).

8. **Cumulo-nimbus** (Cu.-Nb.), the **Thunder Cloud; Shower Cloud.** *Heavy masses of cloud rising in the form of mountains, turrets, or anvils, generally surmounted by a sheet or screen of fibrous appearance (false cirrus) and having at its base a mass of cloud*

Mount Wilson Calif. F. Ellerman

Plate II.—Cirrus, Tufted Form

Mount Weather, Va. A. J. Weed

Plate III.—Cirrus (top half of picture) and Cirro-Stratus (bottom half)

similar to nimbus. From the base local showers of rain or snow (occasionally of hail or soft hail) usually fall. Sometimes the upper edges assume the compact form of cumulus, and form massive peaks round which delicate "false cirrus" floats. At other times the edges themselves separate into a fringe of filaments similar to cirrus clouds. This last form is particularly common in spring showers.

The front of thunderclouds of wide extent frequently presents the form of a large arc spread over a portion of a uniformly brighter sky.

9. **Nimbus** (Nb.), **Rain Clouds.** *A thick layer of dark clouds without shape and with ragged edges,* from which *steady* rain or snow usually falls. Through the openings in these clouds an upper layer of Ci.-St. or A.-St. may be seen almost invariably. If a layer of Nb. separates up in a strong wind into shreds, or if small loose clouds are visible floating underneath a large Nb., the cloud may be described as *Fracto-nimbus* (Fr.-Nb.) ("Scud" of sailors). [Note that all rain clouds are not nimbus (nor Cu.-Nb.), but only those having the characteristics as defined. A.-St., St., and St.-Cu. frequently yield rain or snow, while precipitation occasionally reaches the ground from A.-Cu., Cu., and possibly others.]

10. **Stratus** (St.). *A uniform layer of cloud resembling a fog but not resting on the ground.* When this sheet is broken up into irregular shreds in a wind, or by summits of mountains, it may be distinguished by the name *Fracto-stratus* (Fr.-St.). [St. may be undulated or festooned, even though "uniform." Its evident low height (under 1,000 meters) distinguishes it from nonfibrous A.-St.]

Examples of these types are given in the accompanying plates, II to XI. As a rule, a photograph of the sky shows not a single well-defined type but a combination of two or more types, one often merging into another, as for instance, cirrus into cirro-stratus, cumulus into cumulo-nimbus, etc. Cloud observing presents perhaps more difficulties than does that of any other element, and only the trained observer can identify some of the forms with accuracy.

Altitude. In general the cloud types occur within more or less definite limiting altitudes, and the classification may therefore be said to be in a rough way one of altitude as well as of appearance. A single exception is the alto-stratus type cloud,

which occurs over a wide range with no well-defined height of maximum frequency. From measurements made at Blue Hill, Mass.,[2] the following conclusions were drawn:

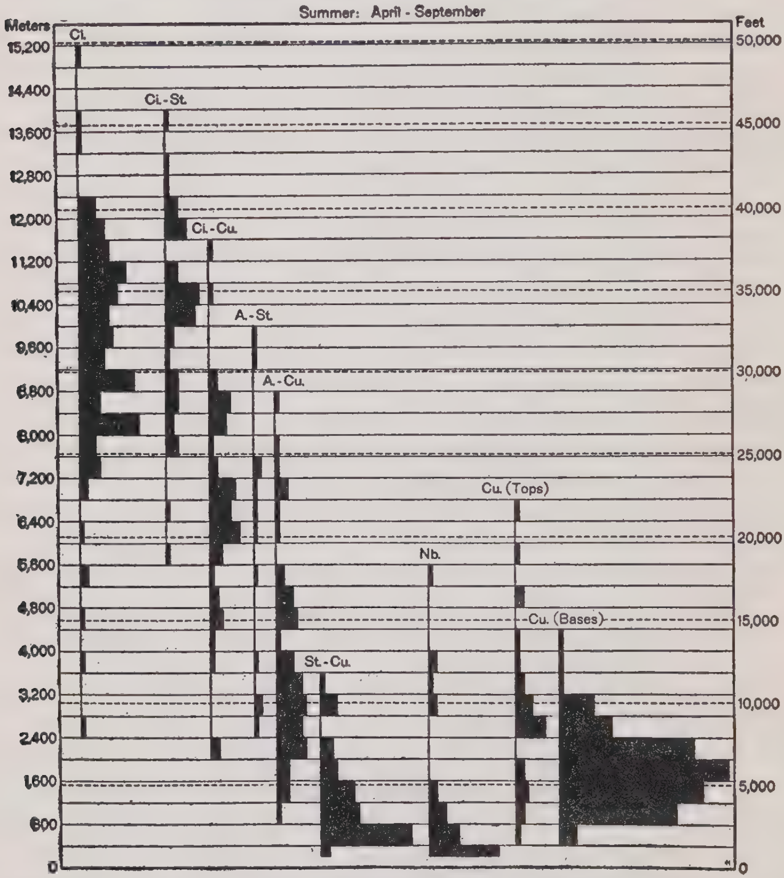

Figure 24. Cloud Height Frequencies, April to September, 1890-91 and 1896-97, Blue Hill, Mass.

Based upon tabulation for each 400 meters by H. H. Clayton. Relative frequency is indicated by width of figure.

Cirrus were measured 227 times. The height of maximum frequency, both summer and winter, was between 8,000 and

[2] Clayton, H. Helm, "Observations made at the Blue Hill Observatory," *Annals of the Astronomical Observatory of Harvard College*, Vol. 40, Part V, p. 253. See also "Cloud Forms," prepared by Weather Bureau Cloud Committee, 1924.

8,400 meters. A secondary maximum frequency was found between 10,800 and 11,200 meters for summer months and between 10,000 and 10,400 meters for the winter months. Seven-

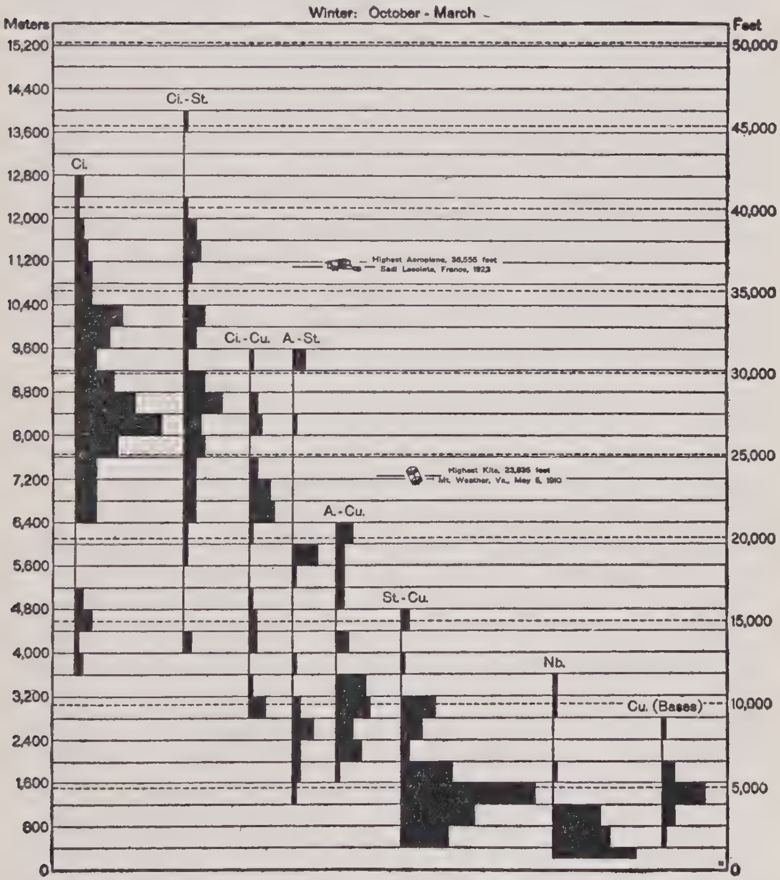

Figure 25. Cloud Height Frequencies, October to March, 1890-91 and 1896-97, Blue Hill, Mass.

Based upon tabulation for each 400 meters by H. H. Clayton. Relative frequency is indicated by width of figure.

tenths of all cirrus observed were found between 7,600 and 11,200 meters; only three instances above 13,000 meters.

Cirrus-stratus. Summer measurements were made of 45 occurrences, of which one-third were between 10,000 and 10,-

800 meters, and the remainder mostly between 8,000 and 12,400 meters. Winter measurements of 58 occurrences showed that they are formed in lower levels than in summer, as they were found all the way from 4,400 to 12,000 meters, with a not very pronounced maximum frequency between 8,400 and 8,800 meters.

The Cirro-cumulus, a form of relatively infrequent occurrence, were found 78 times. Four-tenths of these were between 6,000 and 7,200 meters, the remainder being found about equally above and below these levels.

Alto-cumulus. One-half of those measured during the summer months, and two-thirds those of the winter months, were between 2,000 and 4,000 meters, with the maximum frequency for both summer and winter at 3,000 meters. For summer months, there was a secondary frequency maximum at 5,000 meters, with occasional occurrences up to 8,800 meters. For winter there was a secondary maximum at 6,400 meters with none observed above that level.

The *Strato-cumulus, Cumulus,* and *Nimbus* are comparatively near the ground, mostly below 2,000 meters, and seldom higher than 3,000 meters.

These conclusions are presented in diagrammatic form in Figures 24 and 25.

Thickness. Not much is known as to average and extreme thickness of clouds, but from measurements with kites and captive balloons Peppler [3] gives the following results:

Stratus. Thickness less than 400 meters in greatest number of cases; very seldom greater than 600 meters; mean thickness, 320 meters. There appears to be little seasonal difference.

Nimbus. Mean thickness, 800 meters. This is based on a smaller number of observations, owing to the fact that ascents are difficult when nimbus clouds prevail.

[3] Peppler, W., "Die vertikale Erstreckung der Wolkenschichten und die Wolkentagen über Lindenberg," *Meteorologische Zeitschrift,* January, 1921, pp. 18-21. Abstract by C. L. Meisinger in *Monthly Weather Review,* Vol. 49, pp. 347-348, June, 1921.

Mount Wilson, Calif. E. E. Barnard

Plate IV.—Cirro-Cumulus, Overhead

Orient, L. I., N. Y. W. S. Davis

Plate V.—Cirro-Stratus and Fibrous Alto-Stratus such as Originate from Thunderstorm Tops

Mount Weather, Va.

Plate VI.—Alto-Cumulus

A. J. Weed

Orient, L. I., N. Y. W. S. Davis

Plate VII.—Strato-Cumulus Rolls, with Strong East Wind at Surface (Taken Looking South)

Mount Wilson, Calif. F. Ellerman

Plate VIII.—Nimbus, with Fog or Stratus Below

Topeka, Kans. W. M. Lyon

Plate IX.—Cumulus

Mount Wilson, Calif. F. Ellerman

Plate X. Cumulo-Nimbus, just Grown from Cumulus

Mount Weather, Va. A. J. Weed

Plate XI.—Stratus Clouds at Two Levels; One Practically on the Ground

Cumulus. 89 observations gave a mean thickness of 500 meters.

Strato-cumulus. Layers less than 500 meters in thickness were predominant; mean thickness, 310 meters.

Alto-cumulus and alto-stratus. Mean thickness of A.-Cu., 120 meters. These last figures were based upon comparatively few observations, however.

Cumulo-nimbus clouds were apparently not included in this study. It is well known, though, that their thickness is much greater than is that of any other forms. Hann in his "Lehrbuch der Meteorologie" gives their average thickness as 2,070 meters and their greatest measured thickness as above 4,600 meters.

Diurnal variation. On the average there is a maximum cloudiness about noon and a minimum in the late evening.

Annual variation. In temperate latitudes maximum cloudiness occurs in the winter season, and minimum in the summer and early autumn. The variation is pronounced so far as the nights are concerned; it is less so in the daytime because of the frequency of clouds of the cumulus type during the summer.

CHAPTER VI

VISIBILITY

Horizontal visibility is observed and reported in the United States in accordance with the following scale:

Scale	Descriptive Terms	Limiting distance (meters)
0	Dense fog—prominent objects not visible at	50
1	Very bad—prominent objects not visible at	200
2	Bad—prominent objects not visible at	500
3	Very poor—prominent objects not visible at	1,000
4	Poor—prominent objects not visible at	2,000
5	Indifferent—prominent objects not visible at	4,000
6	Fair—prominent objects not visible at	7,000
7	Good—prominent objects not visible at	12,000
8	Very good—prominent objects not visible at	30,000
9	Excellent—prominent objects visible beyond	30,000

This is the scale originally recommended by the International Meteorological Committee, but in 1921 a change was made in the limiting distances for numbers 6 to 9 from those above given to 10,000, 20,000, 50,000 and 50,000 meters respectively.

In the United States visibility observations are at present made at all aerological stations. The limiting distances are laid off on a large scale map of the country in the vicinity of the station, and prominent objects are selected as points of reference, as nearly as possible at these distances. Some attempts have been made to devise apparatus for determining visibility more precisely, but thus far nothing really suitable has been developed.

The whole subject of visibility is in need of investigation, as it is one of crucial interest to the aeronaut. Such investiga-

tion should be directed toward perfecting methods for accurate observation, both horizontally and vertically, in order that reports may be on a uniform basis. The size and color of objects selected or installed as reference points should be standardized, as well as their direction from the station. Preferably also, more than one direction should be employed, since visibility varies with the wind direction and speed, with the position of the sun at the time of observation and with local conditions. It will probably be found that there will be few laws of wide application; each locality will have characteristics peculiar to itself, in greater degree perhaps than with any other meteorological element. Thus, proximity to large industrial centers, location with reference to bodies of water, large or small, and other topographic features materially influence the visibility of a place. In general it is better in summer than in winter, in the interior than along coasts, in the direction from which a wind comes than in the opposite direction, and in anticyclonic than in cyclonic weather.

Relation to dust content. The lowest visibility is of course caused by dense fog, heavy snow, excessive rainfall and low lying clouds. Other serious factors are dust, smoke and haze. In an "Investigation of the Dust Content of the Atmosphere," [1] the following conclusion was reached as to the relation between dust content and visibility:

"If we take the product of D, the limit of visibility, $R.H.$, the relative humidity expressed as a per cent, and the maximum value of N, the number of particles per cubic centimeter, through which the point at distance D can be seen, or $C = D \times R.H. \times N$, we obtain roughly, $C = 480{,}000$, from which, $D = C/\ (N \times R.H.)$. Of course if N is small, this gives a value of D much larger than that observed, but not more discrepant than we would expect from the nature of the data. More refined methods of determining the limit of visibility are

[1] Kimball, H. H., and Hand, I. F., *Monthly Weather Review*, Vol. 52, pp. 133-141, March, 1924.

needed, and the values of N should be free from local influences."

Vertical visibility. Kimball and Hand, above cited, found that "Surface visibility is a poor criterion of visibility at the ordinary levels of air navigation. After leaving the ground on a morning when objects could be seen at a distance of 20 miles or more, upon reaching a height of 3,000 feet it appeared as though the plane were flying in dense smoke and the visibility decreased to 10 miles.

"On the other hand, on October 30, with light fog and poor seeing at the surface, at 10,000 feet the visibility was 100 miles.

"The visibility from the air is greatly diminished by clouds even in the incipient form."

In a study of vertical visibility, carried on in England,[2] the following conclusions of more or less general application were reached:

"Surface wind velocity bears little relation to the degree of vertical visibility experienced."

"There is a progressive decrease in vertical visibility from low to high wind speeds."

"In general the vertical visibility appears to decrease progressively with increasing low cloud amount."

"Vertical visibility is better upon those days when surface convection currents are present than when they are absent."

"The results of a comparison of the vertical visibilities and ground horizontal visibilities prevailing at the same time showed that the relation between these two elements could only be regarded as slight." [3]

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[2] Pick, W. H., and Peters, S. P., "A Note on the Vertical Visibility Estimated Looking Downwards at Cornwell, Lincolnshire, during the Period February, 1922, to June, 1923," *Quarterly Journal, Royal Meteorological Society,* Vol. 50, No. 209, pp. 53-59, January, 1924.

[3] *Cf.* Kimball's and Hand's conclusion above given.

CHAPTER VII

THUNDERSTORMS

The following excerpts from a paper by the late Dr. C. LeRoy Meisinger[1] give briefly the processes of formation of thunderstorms and the cause of lightning and hail.

Formation. "Thunderstorms are always the result of strong atmospheric convection, which may be initiated either thermally, from intense heating of the surface of the earth, or mechanically owing to the forcing aloft of warm, moist air by an underrunning current of cold, dry, hence heavy, air.

"The type of storm arising from thermal convection is that which is so often observed on hot summer afternoons, when there is but little air movement, and the lower atmosphere is muggy and uncomfortable. Such storms usually move very slowly, and are, therefore, a decidedly local phenomenon. They may occur whenever and wherever the rate of decrease of temperature with increase of altitude is sufficiently great to produce instability.

"Thunderstorms initiated by mechanical convection occur when air of the required temperature and moisture content is lifted above the level it would otherwise occupy. For instance, when a cyclone—and the cyclone must not be confused with the tornado—is passing to the north of a station, a thunderstorm, or a series of thunderstorms along a line, sometimes occur when the cool, dry, and clean northwest wind replaces the southerly wind at the surface. The heavier air underruns the lighter and lifts it in such a manner that a cloud forms, and once condensation has begun, the convection is

[1] "The Thunderstorm and the Aviator," *U. S. Air Services,* January, 1924, pp. 11-15.

accentuated by the heat thus liberated. Such storms occur along a line forming the boundary between the two masses of air, the squall or windshift line which extends in a general southwesterly direction from the center of well-marked cyclones."

Cause of lightning. "The minute water droplets which compose the cloud fall relative to the air in which they float; but, owing to the powerful up-draft, they are carried to higher levels, where, under the action of mechanical and electrical forces, the drops coalesce. The larger and heavier drops eventually succeed in reaching the earth. It has been shown experimentally, however, that when water droplets are of such size that their velocity of fall in air exceeds 8 meters a second (18 miles an hour) they suffer disruption; and, in the case of the violent ascent of air within the cloud, such disruption must occur on a great scale. This blasting of the water droplets gives rise to a difference of electrical potential between the cloud and the earth which is relieved by the lightning discharge."

Cause of hail. "When water drops are lifted above the freezing level, ice pellets are formed, which, when they eventually fall, become coated with water, and if they are again induced into the rising current, the water coating freezes. Eventually the ice pellets become heavy enough to fall through the ascending currents and reach the earth as hail. That such a cycle of rising and falling is many times repeated is shown by the fact that hailstones, when cracked so as to reveal their internal structure, usually show several concentric layers of ice."

Other characteristics. Aside from the lightning and thunder that invariably, and the hail that occasionally, accompany thunderstorms there is usually heavy rain preceded by a squall wind, often of considerable violence. This squall wind

is caused by the rapid descent of cool air within the storm to the surface and the resulting forcing up of the warm air just in front of the storm. There is little turbulence as a rule in the rear of the storm, an occasional exception being noted in the case of a stationary storm, in which convection is more or less active in all its parts, downward in the center, upward in the outer portions.

Figure 26 (taken from "Physics of the Air," p. 360, by W. J. Humphreys) presents an ideal cross-section of a typical moving thunderstorm. As indicated by the arrows, nearly all

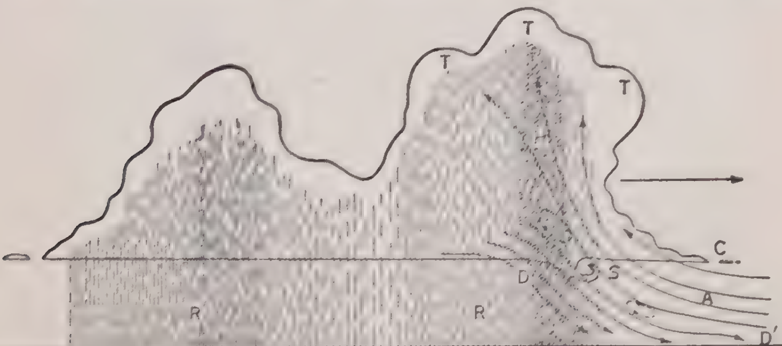

Figure 26. Ideal Cross-section of a Typical Thunderstorm (after Humphreys)

A, ascending air; *D*, descending air; *C*, storm collar; *S*, roll scud; *D′*, wind gust; *H*, hail; *T*, thunderheads; *R*, primary rain, *R′*, secondary rain.

the air entering the cloud does so through its front under-surface. "The warm ascending air is in the region *A;* the cold descending air at *D;* the dust cloud (in dry weather) at *D′;* the squall cloud at *S;* the storm collar at *C;* the thunderheads at *T;* the hail at *H;* the primary rain, due to initial convection, at *R;* and the secondary rain at *R′*. This latter phenomenon, the secondary rain, is a thing of frequent occurrence and often is due, as indicated in the figure, to the coalescence and quiet settling of drops from an abandoned portion of the cumulus in which and below which winds and convection are no longer active."

Table 8.—Average Number of Days With Thunderstorms at Selected Stations in the United States

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Asheville, N. C.	*	1	2	4	7	13	13	11	5	1	*	*	57
Atlanta, Ga.	*	1	3	4	7	10	15	12	5	1	1	1	60
Birmingham, Ala.	1	2	4	5	7	12	15	12	7	1	1	1	68
Bismarck, N. D.	0	0	*	1	4	7	8	6	3	1	*	0	30
Boise, Idaho	*	*	1	1	3	4	4	3	2	1	*	*	19
Boston, Mass.	*	*	1	1	2	3	5	4	2	1	*	*	19
Burlington, Vt.	*	*	1	1	4	6	8	6	3	1	*	*	30
Charleston, S. C.	1	2	2	4	6	9	14	12	7	1	1	*	59
Cheyenne, Wyo.	0	0	*	3	7	11	14	12	5	1	0	0	53
Chicago, Ill.	*	*	3	3	5	8	7	7	5	2	1	*	41
Columbus, Ohio	1	1	3	4	6	9	10	8	4	1	1	*	48
Denver, Colo.	0	0	1	2	6	10	12	12	5	1	*	0	49
Detroit, Mich.	*	1	2	3	5	7	7	6	4	2	1	*	38
Dodge City, Kans.	*	*	1	3	6	9	9	8	4	1	1	*	42
Dubuque, Ia.	*	*	2	3	6	8	7	7	5	2	1	*	41
Duluth, Minn.	*	0	*	1	4	6	8	6	3	1	*	0	29
El Paso, Tex.	*	*	*	1	2	5	9	9	4	2	1	*	33
Fort Worth, Tex.	2	2	4	7	9	8	6	7	5	3	1	1	55
Galveston, Tex.	1	2	2	4	6	5	8	8	7	3	2	2	50
Helena, Mont.	*	0	*	1	4	9	10	8	3	1	*	*	36
Huron, S. Dak.	0	*	1	2	5	9	8	7	4	1	*	0	37
Indianapolis, Ind.	*	1	3	5	6	9	9	7	5	2	2	*	49
Jacksonville, Fla.	1	2	3	4	9	13	19	17	9	2	*	1	80
Kansas City, Mo.	1	1	4	5	8	10	10	9	7	3	1	*	59
Key West, Fla.	1	1	1	3	5	9	11	12	11	4	1	2	61
Lexington, Ky.	1	1	3	4	7	10	11	8	5	1	1	1	53
Los Angeles, Calif.	1	*	1	*	*	*	*	*	*	*	*	*	4
Memphis, Tenn.	1	2	4	6	6	8	9	8	4	2	2	1	53
Modena, Utah	*	*	1	2	3	3	12	12	4	1	*	*	38
Nashville, Tenn.	1	2	4	5	7	10	11	9	5	2	1	1	58
New Orleans, La.	2	2	4	5	7	11	15	15	8	2	1	2	74
New York, N. Y.	*	*	1	2	4	6	8	6	3	1	*	*	31
Norfolk, Va.	*	1	1	3	6	8	9	8	3	1	*	*	40
North Platte, Neb.	0	*	*	2	7	9	10	9	3	1	*	0	41
Oklahoma, Okla.	1	1	3	5	7	9	6	7	5	3	1	*	48
Omaha, Neb.	*	*	1	4	8	9	9	9	6	2	1	*	49
Pensacola, Fla.	2	3	3	5	8	12	16	16	10	3	1	2	81
Philadelphia, Pa.	*	1	1	2	4	6	9	6	3	1	*	*	33
Phoenix, Ariz.	*	1	1	1	1	1	10	10	3	1	1	*	30
Pittsburgh, Pa.	*	1	2	4	6	9	10	8	5	1	*	*	46
Portland, Me.	*	0	*	*	2	3	4	4	2	1	*	*	16
Reno, Nev.	0	*	*	*	2	3	4	3	2	1	0	0	15
Richmond, Va.	*	*	2	3	6	8	10	8	4	1	*	*	42
Roseburg, Ore.	0	0	*	*	1	1	1	1	*	*	0	*	4
St. Louis, Mo.	*	1	4	5	7	8	8	8	5	3	1	*	50
Salt Lake City, Utah	1	*	1	2	4	5	7	8	4	3	*	*	35
San Antonio, Tex.	*	1	3	5	7	4	5	4	5	2	1	1	38
San Diego, Calif.	*	*	*	*	*	*	*	1	*	*	*	*	3
San Francisco, Calif.	*	*	*	*	0	*	*	0	*	*	*	*	2
Santa Fe, N. Mex.	*	*	2	3	7	11	21	18	8	3	*	*	73
Sault Ste. Marie, Mich.	*	0	1	1	2	4	4	4	3	2	*	0	21
Savannah, Ga.	1	1	2	4	7	10	15	13	6	1	*	*	60
Seattle, Wash.	*	*	*	*	1	1	1	1	1	1	*	*	6
Syracuse, N. Y.	*	*	1	2	4	7	8	6	4	2	*	*	34
Tampa, Fla.	1	2	2	3	9	16	22	21	13	3	1	1	94
Washington, D. C.	*	1	2	3	5	8	9	7	4	1	*	*	40
Wilmington, N. C.	1	1	2	4	5	8	12	11	5	1	*	*	50
Winnemucca, Nev.	0	0	*	1	2	3	3	2	2	*	*	0	13

* Less than 1 day in 2 years, on the average.

Note: Numbers indicate days with storms rather than the total number of storms, two or more of which sometimes occur in a single day.

Annual variation. Thunderstorms of the thermal type occur almost altogether in the summer; those mechanically produced are most numerous then, but may occur at any season. The average monthly and annual number of days with thunderstorms at selected stations in the United States, based on a 20-year record, is given in Table 8.

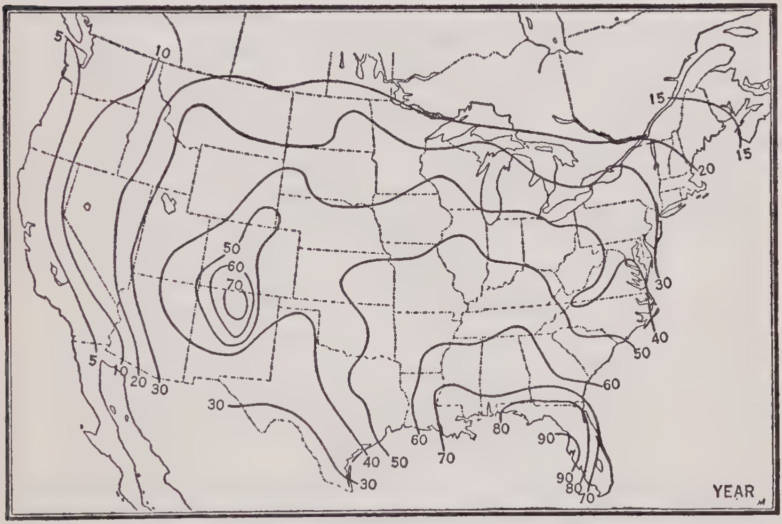

Figure 27. Average Annual Number of Days with Thunderstorms in the United States

Distribution in the United States. Figure 27 shows the average annual number of days with thunderstorms, based upon a 20-year record[2] for all observing stations, including those listed in Table 8. Conspicuous features are the small number along the Pacific coast and the center of maximum frequency in the Florida peninsula, with a secondary maximum at Santa Fe, N. Mex.

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[2] Alexander, William H., "The Distribution of Thunderstorms in the United States." *Monthly Weather Review,* Vol. 52, June, 1924. A notable contribution on the subject of thunderstorm distribution has recently been published by C. E. P. Brooks on "The Distribution of Thunderstorms over the Globe," Meteorological Office, London, M. O. 254d. London, 1925.

Diurnal variation. Thunderstorms on land are most frequent between noon and 5 or 6 P. M., and least frequent between 3 and 6 A. M. In the southern states, those bordering on the Gulf, they rarely occur at night, being mostly of the thermal, i.e., afternoon, type in those sections. At sea thunderstorms occur at night more often than in the daytime.

Height. As stated in the section on clouds, Cumulonimbus have a greater vertical thickness than have any of the other types, the average given being about 2 kilometers and the extreme nearly 5 kilometers. The height of their bases ranges between 1 and 1½ kilometers above the surface, and their tops therefore between 2 and 5 or 7 kilometers. It appears then that, on the average, thunderstorm activity extends to about 3 or 4 kilometers, in exceptional cases to 6 or 7.

Duration. On the average thunderstorms continue for some 6 or 7 hours, but cases have been known in which they lasted more than 12 hours. However, owing to the progressive movement of most storms, the duration at any one place is usually less than 2 hours.

Direction and rate of movement. In temperate latitudes most thunderstorms of the line type move in a general eastward direction in conformity with the upper currents which are from the west in regions of most frequent occurrence of these storms, viz., in the southern part of cyclones. The average rate of movement is 30 to 40 miles per hour (50 to 65 kilometers) in the United States and 20 to 30 miles (30 to 50 kilometers) in Europe. Storms of the thermal type common in the southern states, which often occur when pressure distribution is ill-defined, move more irregularly as to both direction and speed. Those in mountainous regions are sometimes practically stationary.

Area covered. From a very small beginning thunderstorms increase considerably in area, the greatest increase occurring along the front, the ratio of length to width being

somewhere near 4 or 5 to 1, and the actual dimensions 150 to 200 miles (240 to 320 kilometers) in length and 40 to 50 miles (65 to 80 kilometers) in width. In individual cases a still larger area has been noted. The direction of movement is at right angles to the longer axis. Many storms of the thermal type, of slow movement, spread out in all directions instead of merely at the front.

Thunderstorms and flying. Thunderstorms present three principal sources of danger to the aeronaut: (1) The squall wind at the front of the storm; (2) the violent vertical movements within the storm; and (3) lightning. Others of lesser importance are hail, heavy rain and poor visibility.

The squall wind is particularly dangerous in landing and low flying. The danger lies not so much in the initial ascending current which merely carries the aircraft up, sometimes 1 or 2 kilometers, as in the descending current just behind it which causes the craft to drop, as if without support, and to crash if flying low. Cases have been reported [3] in which an attempt to land was made while the aircraft was in one current, but was unable to land without great danger because, by the time the ground was closely approached, the craft was in the other current, i.e., was flying with the wind.

The vertical movements within a thunderstorm are such that no aircraft should ever undertake to fly through such a storm.

Lightning has been known to strike a considerable number of airplanes, in some cases with fatal results. Until recently, however, only one instance had ever been reported of destruction of a free-balloon from this cause, but in the Gordon Bennett Race of 1923 three balloons were struck and in 1924 Dr. C. LeRoy Meisinger and Lieut. James T. Neely were killed when their balloon was either struck by lightning or

[3] Brooks, C. F., and Others, "Effect of Winds and other Weather Conditions on the Flight of Airplanes," *Monthly Weather Review,* Vol. 47, pp. 523-532, August, 1919.

destroyed by an explosion from a static discharge.[4] The danger from this source is thus seen to be a very real one.

Fortunately there is usually a warning, of at least 20 or 30 minutes, of the approach of a thunderstorm, even longer if the aircraft is already in the air. Three courses are then open: (1) Landing at once—if necessary, by first flying away from the storm until a suitable landing place can be found; (2) flying above the storm; and (3) flying around the storm. That the last two courses are often practicable is evident from the fact that during the months June to August in the 2 years 1921 and 1922, the season when thunderstorms are frequent along the New York–Chicago airway, every scheduled flight of the Air Mail Service was made between Cleveland and Chicago, both ways; every one between New York and Cleveland in July; all but one in June and all but two in August. Delays there were in some cases, but rarely complete failures.

A similar problem is presented in the case of free-balloons, since, even without a power plant, the same three courses are theoretically possible. To fly over or around a storm, however, the action must be anticipated far in advance. In order to do this successfully soundings should be made by means of small balloons, inflated with air for the region below the free-balloon, and with hydrogen or other gas lighter than air for the region above. By these means air currents blowing away from the storm can be located without unnecessary loss of ballast or gas. In case soundings can not be made, a free-balloon should, if a storm is approaching, either land or ascend to a height above the top of the storm. If either of these courses is impracticable, it should ascend to about the height of the thunderheads (*TTT* in Figure 26), since the storm advances at approximately the rate of the air currents in which

[4] For an account of this occurrence and an analysis of the data obtained by Dr. Meisinger in his free-balloon flights the reader is referred to "An Account and Analysis of the Meisinger Free-Balloon Flights," by V. E. Jakl, *Monthly Weather Review,* Vol. 53, pp. 99-107, March, 1925.

these clouds form. The chances are good that a balloon at this height will keep ahead of the storm. However, the safest course, as already indicated, is to ascend well above the highest thunderclouds, if that is possible.

Based upon the recent catastrophes from lightning and upon previous personal experiences in the violent vertical currents within the storms, Ralph Upson has recently urged [5] the following practice, so far as free-balloons are concerned:

"All pilots are warned against any attempt to stay up in a thunderstorm. It is preferable to make a landing in any case where a thunderstorm is found to be anywhere in the vicinity. If for good and sufficient reasons it is found necessary to stay up in an electrical storm, or in any case where conditions are doubtful (which applies to any storm of either the convection or line squall type) the following rules must be rigidly adhered to:

1. All radio antennae must be either cut off or packed in the basket.
2. The drag rope must not be dropped until within reach of the ground.
3. Do not touch valve or ballast except when within a few hundred feet of the ground.
4. When once riding on the drag rope (which condition should be sought before entering the storm) spend as much gas or ballast as necessary to stay there.

With reference to Rule 1, the following excerpt from a report by Dr. Meisinger, covering his and Lieut. Neely's flight of April 23, 1924, has a tragic interest in the light of what later happened:

"The (radio) bulletin the next day (April 24th) at 11 A. M. was not listened to, owing to heavy static which not only prevented our hearing more than WOC's time signals but also caused such *violent sparking about the radio set* as to cause us to reel in the trailing antenna and attach it to the counter-

[5] *National Aeronautic Association Review,* Vol. 2, No. 7, July 1, 1924.

poise, which operation was not accomplished without the reception of *violent shocks* by Lieut. Neely." (Italics are the author's.)

Tornadoes. These destructive storms are closely associated with thunderstorms in V-shaped cyclones, though fortunately they are much less frequent. They occur principally in the central Mississippi and Ohio valleys, in some portions of the upper Mississippi valley and in the interior parts of the southern states, and are most numerous in spring and early summer. Though of great violence, both from the high wind velocities and the low pressure at their centers—the latter having an explosive effect upon buildings—they are fortunately of small area, 100 to 500 meters in diameter, and of limited height, less than 1½ kilometers as a rule, and almost invariably travel northeastward. Hence they offer no great problem to the aeronaut, who can readily fly around or over them. The free-balloonist should ascend as rapidly as possible to a height of 2 kilometers or more.

CHAPTER VIII

CYCLONES AND ANTICYCLONES

The most conspicuous features of a weather map are the areas of low and high barometric pressure, called respectively "cyclones," "depressions" or "lows," and "anticyclones" or "highs." There are two general classes of each of these two

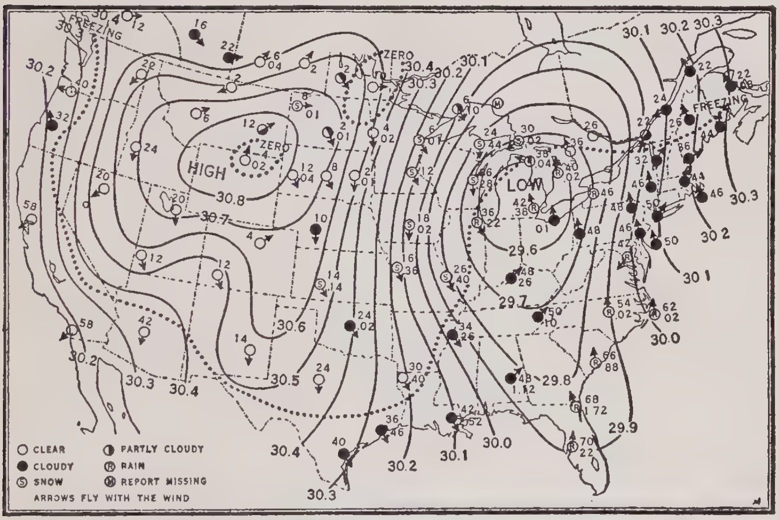

Figure 28. Daily Weather Map, November 28, 1911, Based on Observations at 8 A.M. 75th Meridian Time (after Bliss)

Isobars, solid lines, pass through points of equal air pressure. Isotherms, dotted lines, pass through points of equal temperature and are drawn for freezing and zero only. First figures indicate lowest temperature during last 12 hours; second, 24-hour precipitation when .01 inch or more; third, wind velocity when 10 or more miles per hour.

types of pressure distribution: (1) The more or less stationary areas caused by distinct temperature differences in adjacent regions, e.g., the so-called "Bermuda High," the "Pacific High," and the "Aleutian Low"; and (2) the more

familiar areas that follow one after the other in more or less regular order and that bring to a region over which they pass the successive changes in weather characteristic of temperate latitudes. Examples of the latter class are shown in Figure 28.[1] Although closely associated one with the other, cyclones and anticyclones are widely different in most respects and will therefore be treated separately. One feature common to both, however, is the relation of wind direction to the pressure gradient, first expressed by Buys Ballot.

Buys Ballot's law. "If you stand with your back to the wind, the region of low pressure will be on the left hand in the Northern Hemisphere and on the right hand in the Southern Hemisphere."

That the wind does not blow directly from high to low pressure is owing to the deflective effect of the earth's rotation; that the winds at the surface are not strictly parallel to the isobars is because of friction and viscosity. These influences have been discussed in an earlier section.

In a general way, also, the relation of wind velocity to pressure gradient is of the same order in both pressure systems, i.e., velocity increases as the gradient becomes stronger. However, it is important to recognize that, for the same gradient, latitude and curvature of the isobars, winds are somewhat stronger in anticyclones than in cyclones. Almost invariably the strongest winds are found in the latter, but this is entirely because the gradients there are much steeper than in anticyclones.

Cyclones

General Characteristics. As indicated in Figure 28 above, a cyclone is an area of low pressure, with more or less circular isobars; in-blowing counterclockwise winds at an angle of 20° to 40°; generally cloudy weather and precipita-

[1] From "Weather Forecasting," by George S. Bliss, Bulletin No. 42, W. B. 862, 1925.

tion; and much higher temperature in the eastern than in the western half, in conformity with the wind direction. There are, in individual cases, innumerable variations in all these features. Some very deep lows are nearly circular in form from the center to the outer boundary; others are V-shaped, as in the example given, the longer axis extending in a general north-south direction; still others show a slight bulging in the southern part, a condition that frequently develops into "secondaries." V-shaped lows are characterized by heavy, often driving rains on the east side, with squalls along the central line; on the west side of this line clearing weather prevails, the change from one type to the other being quite abrupt, as a rule. Secondaries travel in the same general direction as the main storm, often at a faster rate. They are accompanied by heavy precipitation, with thunderstorms in the summer season, and occasionally by strong winds. Slow-moving cyclones in general produce more precipitation than do those that travel rapidly. In summer the map frequently shows several nearly stationary, shallow lows, a type accompanied by little wind, but numerous showers and thunderstorms. On the average the frequency of precipitation in different parts of cyclones in the central portions of the United States is approximately that shown in Figure 29.[2] Stations farther east would show a somewhat larger percentage on the east side than is indicated in the diagrams of this figure. It is to be noted that the eastward bulge in the diagram for summer is probably owing in part at least to the weak gradients of that season and the resulting difficulty of precise orientation of the station with reference to the cyclone's center.

An important exception to the usual temperature distribution occurs in winter cyclones that enter the United States from the Pacific Ocean. Here, because of the characteristic difference between marine and continental temperatures, the south-

[2] Jakl, Vincent E., "A Preliminary Study of Precipitation in Relation to Winds and Temperature," *Monthly Weather Review,* Vol. 52, pp. 18-22, January, 1924.

erly winds on the east side of the cyclone are colder than the northerly winds on the west side. With eastward movement, however, the normal distribution is gradually established.

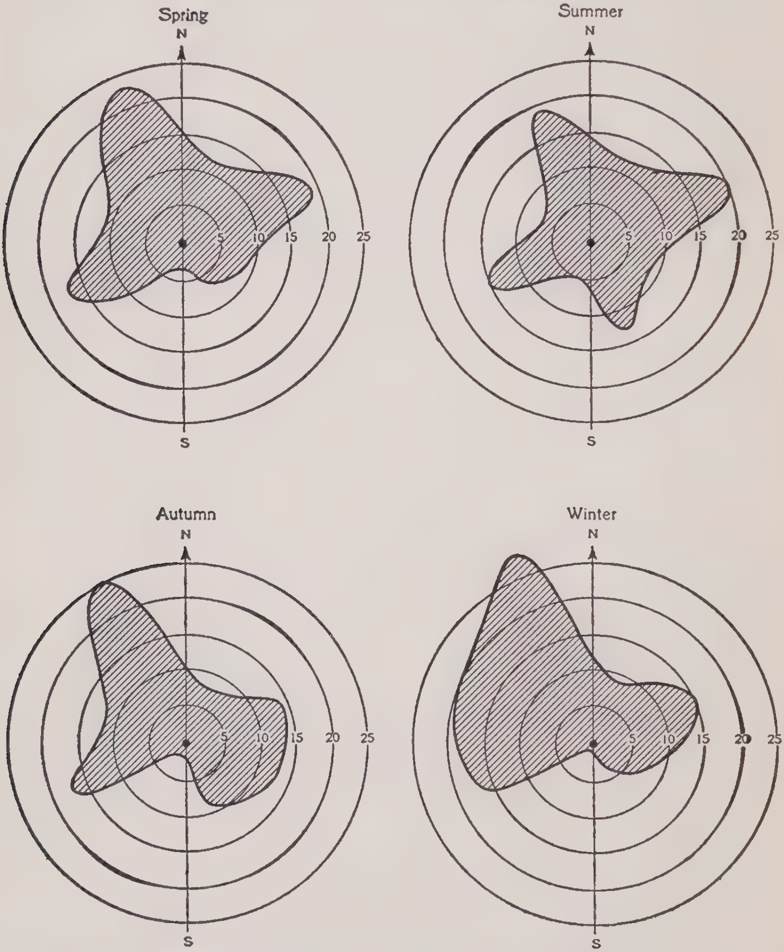

Figure 29. Frequency of Precipitation in Different Parts of Cyclones at Drexel (near Omaha) Neb.
Figures on circles are percentages (after Jakl).

Size. Cyclones vary in size, i.e., extreme limits of influence, from 300 or 400 to 2,000 miles in diameter, with an

average in the United States somewhere between 1,000 and 1,500. They are frequently still larger in the North Atlantic.

Types in the United States. In this country cyclones are classified according to the regions in which they first enter or appear, as follows: Alberta, North Pacific, South Pacific, Northern Rocky Mountain, Colorado, Texas, East Gulf, South Atlantic and Central.

Frequency. The Alberta type is by far the most frequent, constituting nearly two-fifths of the total number. The East Gulf and South Atlantic types are the least frequent. The average number, monthly and annual, for all types combined, is as follows:[3]

Jan.	Feb.	Mar.	Apr.	May	June
13	11	12	10	10	8

July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
9	8	9	10	12	12	124

These figures show that the ratio of winter to summer frequency is about 10 to 7.

Direction and rate of movement. Storms of all types, except those of tropical origin in their earlier stages, travel in a general eastward direction, nearly all in this country passing out across or near the New England states. Those originating in the northern states first move southeastward then northeastward; those in the central and western states, eastward then northeastward; and those in the southern and southeastern states, northeastward. The average annual rate of movement varies from 548 miles per day for the Northern Rocky Mountain type to 656 for the Texas type. In individual cases it ranges from practically zero to well over 1,000 miles. The average monthly and annual 24-hour movement for all types combined is as follows:[3]

[3] From Bowie, E. H., and Weightman, R. H., "Types of Storms in the United States and their Average Movements," *Monthly Weather Review,* Supplement No. 1, W. B. No. 538, 1914.

Jan.	Feb.	Mar.	Apr.	May	June	
745	690	673	542	492	480	
July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
521	489	549	571	646	718	602

Results of numerous studies have shown that the direction and rate of movement of cyclones is approximately that of the upper winds. In the United States the height at which

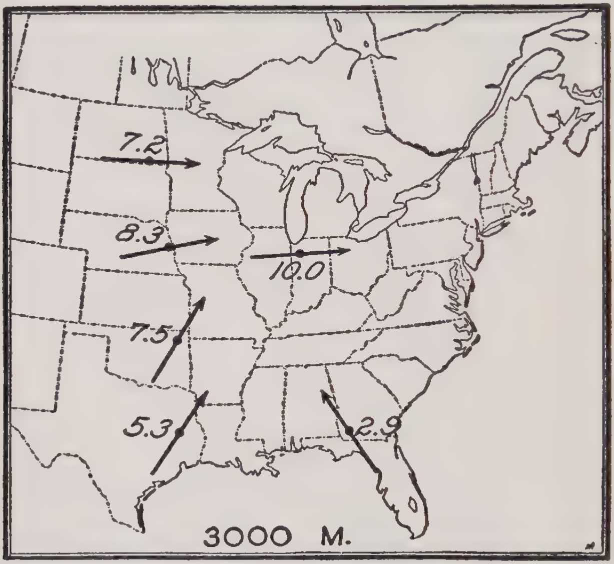

Figure 30. Summer Resultant Winds, m. p. s., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

this relation is on the average closest appears to be about 3 kilometers, as shown by Figures 30 and 31, which give the resultant winds at that height for summer and winter respectively.[4] The average movement of cyclones for summer and winter expressed in m. p. s. (see table next above), is 9.3 and 13.4 respectively; these values agree closely with those presented in Figures 30 and 31.

[4] *Resultant* winds are determined by resolving the observed directions and velocities into their N and W (or S and E) components and adding these algebraically. In computing *average* winds the directions and velocities are considered separately.

Tropical cyclones. These differ in many respects from the cyclones of temperate latitudes. They are of smaller diameter, 50 to 1,000 miles; they are more nearly circular; the pressure gradient is as a rule much steeper, the winds therefore much stronger and the pressure at the center much lower; the "eye" of the storm is well developed, the weather there being clear and the wind light; and they occur in the

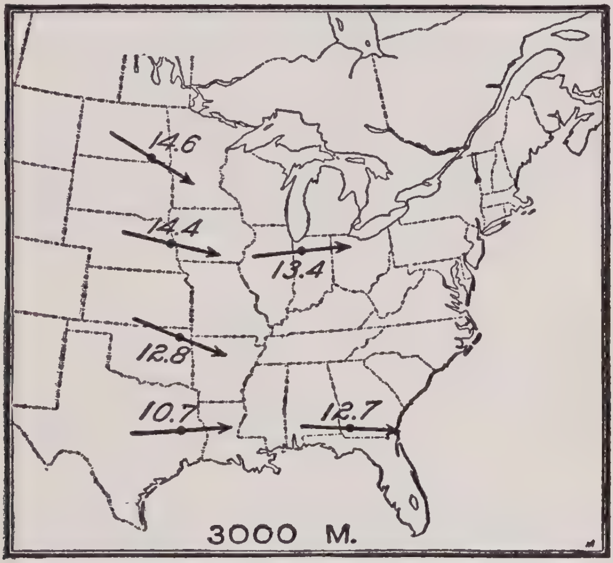

Figure 31. Winter Resultant Winds, m. p. s., in the United States East of the Rocky Mountains at 3 Kilometers above Sea Level

hottest part of the year. In the North Atlantic they are called *hurricanes;* in the Western Pacific, *typhoons;* near the Philippines, *baguios;* and in the Indian Ocean, simply *cyclones.* Hurricanes occur only in the summer half of the year, from June to November, inclusive. The months of greatest frequency are September and October, but many severe storms occur also in August. Since 1878 there has been at least 1 each year, and the maximum number was 16; the average for

this period was 6. Fortunately, however, the number of severe storms that affect the United States is only about one in 2 or 3 years. Those in the early and late months originate as a rule in the western Caribbean Sea; those in the mid-season more frequently near the Cape Verde Islands. The former move northward or northwestward into the Gulf of Mexico, then northeastward, entering the United States along the Gulf coast; the latter, westward, then northward and finally northeastward. In many cases these do not reach the United States but recurve near or to the east of the Bahamas; those that reach the Caribbean Sea usually follow thereafter very much the same course as the ones that first originate there. Fortunately the storms that enter this country soon increase in area and decrease in intensity, assuming the characteristics of the ordinary cyclones.

Anticyclones

General Characteristics. As indicated in Figure 28 above, an anticyclone is an area of high pressure, with more or less circular isobars; out-blowing, clockwise winds at a much larger angle to the isobars than in lows, almost 90° near the center; generally clear weather; and lower temperature in the eastern than in the western half. Owing to the clear weather, the loss of heat by radiation is greater than the amount received from insolation, with the result that anticyclones are cooler in summer than cyclones and much colder, with "cold waves" at times, in winter. Although clear weather is the rule, light rain occasionally occurs in the southern and western quadrants and light snow in the eastern half. Occasionally also fog forms in winter and light precipitation with thunderstorms in summer in the saddle, or "col," between two anticyclones, owing to mixing of the air circulating around the two centers.

Size. Well-defined anticyclones are never as small as the smallest cyclones, and many of them cover a larger area than the largest cyclones; in some cases they have dominated conditions in practically all parts of the United States. In general, however, they vary roughly between 700 or 800 and 2,500 miles in diameter.

Types in the United States. The same basis of classification is used as with cyclones, viz., the region of entry or development. The types are: North Pacific, South Pacific, Alberta, Plateau and Rocky Mountain Region, and Hudson Bay.

Frequency. Again, the Alberta type is by far the most frequent, constituting 50 per cent of the total number. The Hudson Bay and South Pacific types are least frequent. The average number, monthly and annual, for all types combined, is as follows:[5]

Jan.	Feb.	Mar.	Apr.	May	June
9	8	8	8	7	5

July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
7	7	8	8	8	9	92

The ratio of summer to winter frequency is about 2 to 3; and of all anticyclones to all cyclones, about 3 to 4.

Direction and rate of movement. Anticyclones move in a general eastward direction, but somewhat farther south as a rule than cyclones. The Hudson Bay type usually follows a southeastward course. The majority of all types leave the United States along the Middle Atlantic coast. The average annual rate of movement is about 450 miles per day for the Hudson Bay type and about 550 for the other four types. The range is about the same as that of cyclones, zero to 1,000 miles, but a larger proportion move slowly, occasionally remaining practically stationary for a week or more. The average

[5] From Bowie, E. H., and Weightman, R. H., "Types of Anticyclones of the United States and their Average Movements," *Monthly Weather Review Supplement*, No. 4. W. B. No. 600, 1917.

monthly and annual 24-hour movement for all types combined is as follows:[5]

Jan.	Feb.	Mar.	Apr.	May	June	
624	588	585	545	521	484	
July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
483	487	545	548	562	570	544

The average summer and winter speeds, expressed in m. p. s., are 9.0 and 11.1 respectively, somewhat less than those of cyclones. The latter were found to agree closely with the resultant winds at about 3 kilometers, Figures 30 and 31. It is evident then that anticyclones do not reach as great a height on the average as do cyclones. Mitchell[6] has found that "the rate of movement of the anticyclone is roughly proportional to the speed of the free-air winds at and above the 2,000-meter level."

Free-Air Conditions in Cyclones and Anticyclones

Since winds blow at an angle to the isobars in the lower levels (see Figure 28) it follows that the air has an upward component in cyclones and a downward component in anticyclones. This results in cooling of the air in the former and warming in the latter, which processes are responsible for condensation in the first and evaporation in the second. Other conditions being equal, we should expect to find cyclones colder than anticyclones, but importation of air from warm and cold regions modifies and in many instances overcomes the thermal effects of vertical movements. Considered as units, cyclones appear on the average to be colder than anticyclones in Europe except near the surface. In the eastern part of the United States they are warmer up to 2 kilometers and about the same

[5] From Bowie, E. H., and Weightman, R. H., "Types of Anticyclones of the United States and their Average Movements," *Monthly Weather Review Supplement*, No. 4. W. B. No. 600, 1917.

[6] Mitchell, Charles L., "Relation between Rate of Movement of Anticyclones and the Direction and Velocity of Winds Aloft (West and Southwest of Highest Pressure)," *Monthly Weather Review*, Vol. 50, pp. 241-242, May, 1922.

temperature between 2 and 5. In the interior, however, cyclones continue warmer from the surface to 5 kilometers although the difference is not large above 3. These statements refer to the air vertically above the surface positions of the cyclonic and anticyclonic centers. In reality, owing to the effects of temperature on air density, the lowest and highest pressures in the free air are considerably shifted from their surface positions, northwestward in cyclones and southwestward in anticyclones, the amount of the shift depending on the steepness of the horizontal temperature gradient. In the upper levels, moreover, owing to the straightening out of the isotherms, the isobars gradually open out into broad sweeping curves. These changes occur at comparatively low altitudes, 1 to 3 kilometers, if the temperature contrast is large; therefore cyclones and anticyclones are seldom symmetrical to any great height in winter. In summer, if temperatures are comparatively uniform over much of the country, cyclones and anticyclones extend as such to great heights; in general, tropical cyclones reach greater altitudes than do those in temperate latitudes for the same reason.

The turning of winds with altitude has been discussed in an earlier section and it is only necessary to apply the general principles there given to the surface winds appropriate to different parts of cyclones and anticyclones. For example, the southeasterly winds east of a cyclone veer to southwesterly in the upper levels because the lowest pressure shifts northwestward with altitude from its surface position. The normal wind distribution in the upper levels is then southwest to west-southwest over the major part of cyclones and northwest to west-northwest over the major part of anticyclones. The winds above cyclones are strongest in the southern part and weakest in the northern; above anticyclones the opposite relation holds, although the difference between the northern and eastern parts is slight.

The wind circulation thus set up by temperature distribution

in the lower levels in turn affects the temperature distribution in the upper levels. It has been observed that the south component winds above the surface positions of cyclones cause higher temperatures there than are found above anticyclones, where north component winds prevail. The difference is greatest in the interior of the country during the winter when latitudinal temperature contrasts are large. At all levels in the troposphere it is found in general that the region where pressure is rising, i.e., where air movement is from a northerly direction, is colder than that in which pressure is falling.

CHAPTER IX

WEATHER FORECASTING

The Daily Forecast

Meteorological organizations serve two main purposes: (1) The collection of statistical information, of value as such for climatological summaries, and also useful and necessary in explaining the physical causes of various phenomena and, as a direct consequence, in increasing the accuracy of weather forecasting. (2) The furnishing of current information and forecasts of immediate practical value. The successful forecaster applies his knowledge of statistics and the general principles based thereon to the information of current conditions, and the more complete both types of information are the more accurate the forecast will be.

The information of current conditions is entered on weather maps and these constitute the forecaster's working tools. The manner of preparing them, in the United States, is stated briefly below.

Assembling the data. There are about 200 regular observing stations in the United States and about 30 in Canada at which observations of pressure, temperature, humidity, precipitation, state of the weather and wind direction and speed are taken twice daily, 8 A. M. and 8 P. M., 75th meridian time. At this same hour the Western Union Telegraph Company sets up individual wires called "circuits," connecting a majority of the principal observing stations in the United States, with two contact points in Canada, Toronto and Winnipeg. There are 23 of these "circuits" averaging about 750 miles in length, the longest being 1,340 miles and the shortest 231 miles. From

6 to 12 stations are on a circuit, with a telegraph operator at each point. Several circuits terminate at the same station to facilitate the transfer of reports from one circuit to another. For example, one circuit extends from Washington to St. Louis connecting 11 stations, including Chicago, St. Louis, Springfield, Indianapolis, Terre Haute, Evansville, Cincinnati, Dayton, Columbus, Pittsburgh and Washington. Promptly at 8 o'clock the Washington observation is sent over the circuit and every operator along the line copies it. This is immediately followed in fixed order by the observations from other stations thereon. Simultaneously the same operation is being followed on other circuits. As soon as the reports of all stations on a circuit are sent, reports collected at the termini are transmitted to other circuits. By this arrangement of collection and transfer all reports are distributed to stations throughout the country by 9 o'clock as a rule and sometimes a few minutes earlier. In other words, in about an hour from the time of taking the observations they are received and charted ready for the forecasters.

In addition, numerous reports are received daily by cable and radio from Europe, the Azores, the West Indies, Central America, Mexico, Alaska, the Far East and from ships in the Atlantic and the Pacific and in the Gulf of Mexico.

Since December 1, 1918, there have been included also reports of pilot balloon observations made at 16 Weather Bureau stations and about the same number of Army and Navy stations. These give the wind direction and velocity at the surface, at 250, 500, 1,000, 1,500, 2,000, 3,000 and 4,000 meters above it and at the highest altitude reached; the amount, kind and direction of clouds, also their height and velocity, if reached by the balloon; and the visibility.

The weather map. The data thus furnished are entered upon a base map of the United States similar to the one shown in Figure 28, except that it includes a larger area thus permitting the entering of reports from Canada, Mexico, Ber-

muda and the West Indies and Caribbean Sea regions. On this map circles indicate the locations of stations; each circle shows the character of the weather, no shading for clear, half shading for partly cloudy, full shading for cloudy, R for rain and S for snow. Near the circle are entered the current pressure, temperature, and wind velocity, 12-hour precipitation, and the occurrence of thunderstorms, fog and frost. An arrow through the circle shows the direction of the wind. As soon as all the data are entered, lines of equal pressure, isobars, for each one-tenth of an inch (.05 at the center of low-pressure areas) and of equal temperature, isotherms, for each 10° F. are drawn. In addition, the progressive movement of an active low or high is indicated, and occasionally the border line between southerly and northerly winds (the so-called "polar front," of Bjerknes).

Auxiliary charts. The forecaster regularly uses five additional charts on which are indicated the 12-hour pressure changes; the 24-hour temperature changes; upper and lower clouds (on this chart also shading indicates the regions in which precipitation was occurring at the time of observation); pressure and temperature over the Northern Hemisphere so far as reports are available; and wind direction and speed at certain levels in the free air, eight small maps on this chart representing the selected levels.

Making the forecasts. With the data thus charted before him and using his knowledge of the physical principles governing atmospheric movements, seasonal variations, topography and climatic characteristics of different regions, and the previous history of the formations shown on the charts, the forecaster makes his predictions for the portions of the country for which he is responsible. The general forecasts specify the type of weather, the temperature changes and the direction and speed (Beaufort scale) of the wind. Included with these is the expected occurrence of thunderstorms, heavy rain or snow, fogs, frosts and cold waves. Special forecasts warn of

storms and gales along the coasts and on the Great Lakes; of unfavorable weather for planting and harvesting; and of frost in cranberry and other fruit-growing sections. Flying weather forecasts indicate the weather and the free-air wind conditions expected and often the best altitudes for flying.

District forecast centers. For purposes of general forecasts the United States is divided into the five districts shown in Figure 32. The forecasts for these districts are issued at Washington, Chicago, New Orleans, Denver and San Francisco.

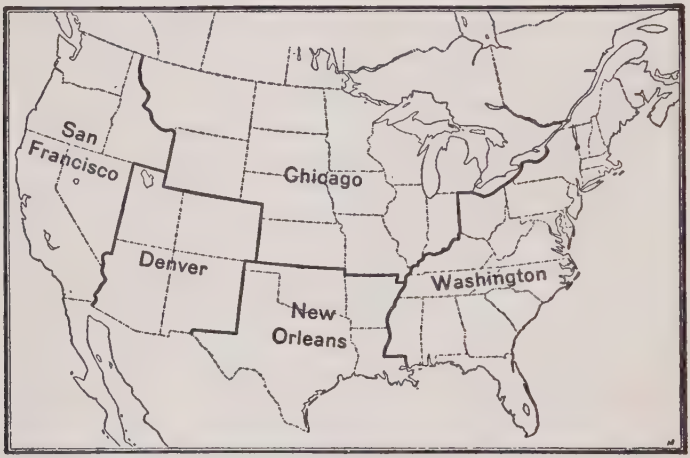

Figure 32. Forecast Districts in the United States

Aviation forecast zones. Forecasts for aviation are made for 14 zones, as indicated in Figure 33. At the present time these forecasts are issued from Washington, Chicago and San Francisco (see legend at bottom of figure).

Dissemination of forecasts. The forecasts for the various districts are usually completed by 10 A. M. or 10 P. M., 75th meridian time. They are then given to representatives of the press and printed in the next edition of the papers; telegraphed to various interests requiring them, such as shippers, aviation

fields, etc.; also to other Weather Bureau stations where they are further distributed by telephone and radio. In addition, at the district forecast centers and at some additional stations maps showing isobars, isotherms, precipitation, character of the weather and wind direction and velocity are printed (see Figure 28) together with statistical tables, a brief general

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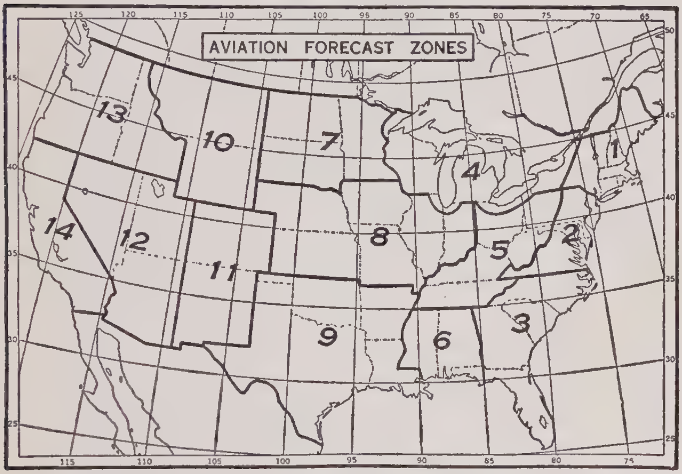

Figure 33. Aviation Forecast Zones in the United States

Forecasts of weather conditions and of wind at surface and aloft are issued twice daily for the benefit of aviators. They are made at 9:30 A.M. and 9:30 P.M. (75th meridian time), and cover a period of 12 hours, beginning at noon and midnight, respectively.

The forecasts for the various zones are prepared and issued from forecast centers of the Weather Bureau as follows:

Washington, D. C.: Zones 1, 2, 3, 5, 6, 9, and 11.
Chicago, Ill.: Zones 4, 7, 8, and 10.
San Francisco, Calif.: Zones 12, 13, and 14.

synopsis of the weather and the forecasts. Officials at many of the stations are authorized to amplify the local forecast. These printed maps are usually completed by 11 A. M. (they are not issued at night) and mailed or distributed by messenger to boards of trade, post offices, large commercial establishments, etc. In some cities a further dissemination of weather information and forecasts is made through the medium of large glass

weather maps. Speed in getting the forecasts to the public is a prime requisite, and therefore all of these various agencies are employed. It is probable that future development of radio broadcasting will even further cut down the interval between the time when the information is available and that when it is received.

Forecasting Precepts

The successful forecaster regards each day's weather map as a problem in itself, differing in many respects from every other map that has ever been presented for his diagnosis. A cyclone of one day may appear to be almost exactly like one of some other day, but closer study will reveal important differences as to previous history and movement, pressure distribution in adjacent regions, etc. Nevertheless, certain general precepts have been developed from years of experience, and these are always extremely helpful, providing sole dependence is not placed upon them. A few of the many that have been found of real value are therefore given here. With some it is necessary to know the prevailing pressure distribution as presented on a weather map; others are based on local indications, and are useful in amplifying the general forecast or in furnishing a prediction when a weather map or a forecast based thereon is not available.

Movements of lows and highs and accompanying surface weather changes. The following precepts have been selected for the most part from a much larger number collected (many of them originated) by Major E. H. Bowie.[1]

1. The paths of storms crossing the United States shift with the position of the Aleutian Low. When after a period of indifferent pressure within the Aleutian area the pressure in this region begins to fall, a low will appear within 36 hours north of Montana and, as the Aleutian Low deepens, lows

[1] Bowie and Weightman, loc. cit., "Types of Storms, etc."

will follow each other in rapid succession along the northern border until the pressure has begun to rise north of the Aleutian area and it (the Aleutian Low) has moved south of its normal position when the tracks of lows in the United States will shift to lower latitudes. Finally, when the Aleutian Low reaches its southernmost position, lows crossing the United States will make their appearance in the southern plateau region or over the Gulf of Mexico.

2. In determining a possible deviation from a normal course, unequal pressure distribution in the regions adjacent to the storm center, the region of maximum 12-hour pressure fall, and the trend of the isotherms should be carefully considered. Also, the magnitude of the rise and fall in pressure in the surrounding regions should be carefully noted, as it is a well-established rule in forecasting that the rate of movement of a storm center has a direct relation to the magnitude of the pressure fluctuations as shown by the pressure-change chart.

3. When there is an area of high pressure over the southeast and a cold wave in the northwest threatens, there will be a storm development in the southwest and precipitation will be general.

4. When a northwest low shows greatest pressure fall in the middle Rockies, the main storm will appear in the southern end of the trough in 24 hours, forming the southern end of the trough rather than having a circular form.

5. Troughs of low pressure moving from the west are of two types, the narrow and the wide. The former moves eastward slowly and storm centers form in the extreme northern and the extreme southern ends. They never form in the middle of the trough where it is narrowest, but do form where the isobars of approaching and receding highs bend away from each other. When the trough is wide, the development of an extensive storm area is not uncommon, especially if the wide

intervening area between the highs shows relatively high temperatures.

6. An area of high pressure moving southward or southeastward in advance of a storm indicates an increase in the storm's intensity.

7. There are indications that pressure-fall areas moving southward diminish and are indicative of cool weather. They occur when pressure is low over the western Atlantic Ocean. Areas of pressure-rises moving southeastward on the map are indicative of warm and dry weather to the east and southeast of the following area of falling barometer. Pressure-rises moving southward and southeastward indicate fair weather, while those moving eastward and northeastward indicate unsettled weather.

8. When the pressure rises on the south and southwest of a high, it indicates a further building up of the high and its slow movement, usually toward the southeast.

9. The position of the area of maximum 12-hour pressure change is very significant for future storm developments. Pressure-fall in the rear of a storm indicates slow clearing and slow movement of the storm. When the pressure-fall is great and the center of greatest fall is near the storm center, a rapid increase in intensity may be looked for.

10. When the southern end of a pressure trough swings eastward faster than the northern end, there is a great probability that a secondary will develop south or southeast of the northern center.

11. As a rule, when the pressure is high north and northeast of a storm it will remain stationary or move very slowly and will be a good rain producer.

12. With a low between two highs, one in the west and the other in the east, it will move rapidly to the northeast, provided its center is north of a line drawn through the centers of the highs. Should the storm center lie south of this line, it frequently happens that the western high moves eastward

and the low is penned in. In this case it may remain stationary several days. The former movement may be accomplished with the rain area running well to the northward. In the latter case it will remain close to the storm center.

13. The movement of a storm directly northward is unusual and seldom occurs except when the pressure is abnormally high east and northeast of its center and is increasing This movement is attended by a marked increase in the storm's intensity and the rain area runs far to the northward.

14. Marked changes in temperature in the southeast and northwest quadrants imply an increase in the storm's intensity. Small temperature changes do not indicate a further development of the storm.

15. Abnormally high temperatures northwest of a storm indicate that the storm will either retrograde or remain stationary.

16. Storms with circular isobars and small centers (that is, inner isobar small) usually move slowly and toward the northeast despite what the pressure distribution indicates.

17. Storms that have steep barometric gradients on their western sides and not on the eastern are invariably slow movers if pressure at the centers is decidedly low.

18. Storms with isobars closely crowded in the south and southeast quadrants move rapidly northeastward and the weather quickly clears after the passage of the storm center. Another type of fast moving storm has the isobars close together immediately east of the storm center; it gathers marked intensity as it moves rapidly eastward. In this case the difference in pressure east and west of the storm is about the same but the pressure gradient adjacent to the storm center is much steeper on the east than on the west of it.

19. A high around which the isobars are elliptical and whose major axis assumes various positions may be designated a "pivoted high." Such highs are frequently seen on the weather map, and the shifting of the major axis is often in-

dicative of weather conditions for several days in advance. For instance, if the northern end of the major axis of a high is pivoted in the northwestern states while the southern end is swinging rapidly eastward, rain or snow with slowly rising temperature follows in the middle Mississippi Valley and the southwest. If, however, the southern end of the major axis of a high remains fixed in position while its northern end is moving eastward, fair weather follows for several days.

20. Areas of high pressure east of the Rocky Mountains around which the isobars are circular or nearly so are usually followed by rain or snow. They move rapidly and usually toward the northeast or east.

21. Lows follow the general trend of the surface isotherms, and their rate of movement increases with increase in the horizontal temperature gradient.

Movements of lows and highs and accompanying changes in free-air winds. From studies of free-air records the following general rules have been developed: [2]

1. With a distant low approaching from the southwest and little pressure variation anywhere, a typical summer condition, surface winds are easterly and shallow, and above them is a layer about 1 kilometer in depth in which there is little or no wind; above this layer southwesterly winds prevail.

2. As a low passes north of the station, and in a general eastward direction surface winds are successively southeast, south and southwest, and the turning of wind with altitude is clockwise, the upper winds nearly always being southwest to west.

3. With a low northeast of the station and a high southwest, both surface and upper winds are northwest. As this high approaches and passes south of the station the surface winds are successively west-northwest, west and west-southwest, turning clockwise with altitude to northwest.

[2] Gregg, W. R., "Turning of Winds with Altitude," *Monthly Weather Review*, Vol. 46, pp. 20-21, January, 1918.

4. With a high east of the station and a low approaching from the west or west-northwest, winds are southwest and strong both at surface and aloft.

5. With a high north of the station and a low approaching from the southwest and passing south of the station, surface winds are north-northeast to east-northeast and there is little turning up to 3,000 meters; the turning at higher levels is in general counterclockwise to north-northwest and northwest.

6. With a high northwest and a low south of the station, surface winds are north to northeast turning clockwise with altitude to northeast, and at higher levels counterclockwise back to north-northwest.

7. With a high northwest and a low passing northward east of the station, surface winds are successively north, north-northwest, and northwest, turning counterclockwise with altitude to northwest and west-northwest.

8. In general, the turning of winds with altitude is usually such that they have a westerly component before the 3-kilometer level is reached. This is almost invariably the case during the winter half of the year; in summer it is also the prevalent condition, though somewhat less pronounced.

Significance of barometer and wind direction. In case a barometer, either mercurial or aneroid, is available, the following table will be found useful:[3]

Barometer	Wind from	Weather Indicated
High and steady	SW to NW	Fair and little temperature change for 1 to 2 days
High and rising rapidly	SW to NW	Fair followed by warmer and rain within 2 days
High and falling slowly	SW to NW	Rain in 24 to 36 hours
Very high, falling slowly	SW to NW	Fair and slowly rising temperature for 2 days
High and falling slowly	S to SE	Rain within 24 hours

[3] In "Weather Proverbs and Paradoxes," by W. J. Humphreys, p. 65, 1923; adapted from a table originally prepared by E. B. Garriott.

Barometer	Wind from	Weather Indicated
High and falling rapidly	S to SE	Increasing wind with rain in 12 to 24 hours
High and falling slowly	SE to NE	Rain in 12 to 18 hours
High and falling rapidly	SE to NE	Increasing wind with rain in 12 hours
High and falling slowly	E to NE	Summer and light winds, fair; winter, rain in 24 hours
High and falling rapidly	E to NE	Summer, rain in 12 to 24 hours; winter, rain or snow with increasing winds
Low and falling slowly	SE to NE	Rain will continue 1 or 2 days
Low and falling rapidly	SE to NE	Rain and high wind; clearing and cooler in 24 hours
Low and rising slowly	S to SW	Clearing soon and fair several days
Low and falling rapidly	S to SE	Severe storm soon, clearing and cooler in 24 hours
Low and falling rapidly	E to N	Northeast gales with heavy rain or snow, followed in winter by cold wave
Low and rising rapidly	Going to W	Clearing and colder

Local forecasting from clouds. The following excerpts are taken from notes furnished by Dr. C. F. Brooks on the prognostic value of clouds:

1. Those who are so situated that they cannot receive the U. S. Weather Bureau's forecasts either directly by radio or indirectly from a distributing center, by telephone, newspaper or mailed weather map can nevertheless use local indications to good advantage in anticipating weather changes. Observations of atmospheric pressure, winds, clouds, sky colors, temperature and humidity, are all of value as prognostics. During a storm, changes in the character of the falling snow or rain also herald different weather. The observer who is without instruments is by no means helpless, as is evident from the local success attained by those who closely watch and remember the changing aspects of the sky. Unfortunately many rules that apply at one place may not be of value at another. He who

keeps his own record of clouds and weather can soon discover useful prognostics for important changes.

2. Squall prognostics, sharp mammato-cumulus (a cloud with mammillated lower surface, often occurring in connection with severe local storms), a low arch cloud, or the approach of a solid-looking rain-front. The squall from a thunderstorm reaches forward usually not more than 5 miles from the rain-front, and it usually blows out perpendicularly from the rain-front. Squalls occasionally occur in strong southerly winds when they come down to the surface.

3. Cloud movements at high velocities from southerly directions, may indicate forced ascent and coming rain, but the presence of such winds even at moderate elevations does not necessarily indicate similar winds for the surface. Such winds are usually considerably warmer than the surface air, and therefore, there is little tendency for a strong southerly wind to come down. On the contrary, strong northerly winds and hard-looking cumulus or strato-cumulus clouds at moderate elevations, are practically infallible signs of a coming gale at the surface, for although at first the temperature gradient is not as great as the adiabatic, only a few hours of such air movement from the cooler north will suffice to produce a tendency to a superadiabatic gradient, with the accompanying rapid interchange of air between the surface and the overrunning cold wind. The appearance of gradually thickening cirro-stratus, then alto-stratus with heavy lines converging in the direction from which they come indicates that an intense cyclone is approaching and that in the normal course of its movement gales will be upon the observer.

4. Morning stratus clouds from the south usually are a prognostic of a marked rise in temperature, for it is formed by the mixture of warm moist air aloft with colder, surface air. Alto-cumulus clouds in the evening when the wind is south are more likely to last all night, or to increase than more or less similar clouds when the wind is northwesterly,

for in the first case it is usually the southerly wind that is responsible for their formation, while in the second, such clouds may be merely the left-overs of flattened tops of convectional clouds formed during the daytime convection from the surface.

5. The speed of movement of the high, cirrus (white, feathery or hairy) clouds is usually a good index to the changeableness of the weather. When these clouds are moving fast, foul weather, i.e., wet or windy weather or both and a sudden change in temperature is likely to follow soon after fair weather. When they are moving very slowly or seem to be standing still, settled weather is to be expected for at least a day or two. Movement of cirrus clouds from the south or southeast should be looked on as cautionary signals, for high clouds from this direction are usually flowing out from the top of an intense cyclone or West Indian hurricane. Another hurricane cautionary warning is the occurrence of a brilliant fire-colored sunset light reflected from the under-surface of clouds for a period of a few minutes shortly after sunset.

6. Of more immediate interest is any advance information as to how soon a brewing thunderstorm may strike. In a period when afternoon thunderstorms are occurring or are expected, the direction of motion and the apparent speed of the fleecy, alto-cumulus clouds should be noted. If, for example, the motion is from the west-northwest, any large cloud heaps or arched tops of thunderstorms in that direction should be watched closely. If the alto-cumulus clouds have been moving fast, shelter should be sought soon, but if they have been going slowly a distant storm may not arrive for 2 hours. Furthermore, if a large thunderstorm is seen approaching apparently from the north-northwest, even if the alto-cumulus clouds have been observed moving rapidly from the west-northwest the storm is not likely to break as soon as might be expected, for the nearest portion of the storm is not coming toward the observer. Under such conditions, however, the

squall will come from the northwest and is likely to prevail for an appreciable interval before rain begins.

7. In the early morning the occurrence of low clouds moving rapidly from any direction, but particularly when from northwest or north is a good indication of a day with strong winds from the direction from which the clouds are moving.

8. Slow cloud movements, especially of cirrus from easterly directions accompany and precede settled weather, usually dry. The entry of a northwesterly wind above a southwesterly wind at the ground is usually a precursor of a shower.

Local forecasting at Naval Air Stations. Lieut. J. B. Anderson, U. S. N., Aerological Officer with the U. S. S. Airship *Shenandoah,* and Lieut. F. W. Reichelderfer, U. S. N., Aerological Section, U. S. Navy, have kindly furnished the following summary of indications that have been found of value in local forecasting at Naval Air Stations, in connection with the operation of airplanes and airships:

A. Local thunderstorms when the synoptic chart is flat and the weather hot.

1. If *alto-cumulus castellatus* (globular masses developing upwards into hard-edged clouds like miniature cumulus) appear in appreciable quantity, at least two-tenths of the sky being covered with them, and if they spread and persist for an hour or more, thunderstorms in the near vicinity are to be expected within 4 to 8 hours. The more characteristic the cumuli, the more probable the storms. Care must be taken not to mistake for the castellatus the small alto-cumulus which form and dissipate with ragged tops. The castellatus usually appear in long strips. It seems that the time of day is also important for several instances have been noticed when alto-cumulus castellatus formed in the late afternoon and were followed by rain only. When this cloud form is observed, other features are watched closely.

2. When the globular alto-cumulus appear in considerable

quantities, thundershowers usually follow. This type has greater vertical than horizontal thickness. It indicates instability and close watch must be kept for the formation of cumulo-nimbus on the horizon. This globular alto-cumulus is known as alto-cumulus glomeratus (Clayden).

3. In central New Jersey, local thunderstorms seldom form until the visibility has become poor through the formation of a haze which is very characteristic. Only passing interest is taken in the formation of cumulus if this haze has not formed. But when it forms, close watch is kept even though no large cumulus have been observed.

4. Local thunderstorms do not often occur when alto-cumulus of the flat variety cover the sky. These are called alto-cumulus maculosus. So long as they exist, only the most violent conditions can cause a cumulus to extend its top above them, and at such times the towering head can be seen a long time in advance. The accompanying storm is generally severe.

5. Local, or "heat" thunderstorms seldom occur if the whole sky is covered with a sheet of cirrus haze. Cumulus may form, but they seldom develop to the extent of showers or thunderstorms.

B. Other thunderstorm indications.

6. Cyclonic thunderstorms, sometimes called tornadic thunderstorms, which occur under conditions similar to the line squall, ordinarily are not governed by the indications mentioned under 1 to 5, above. However, they generally give long warning, usually several hours, by the height and extent of the "anvil" at their tops. This may be observed a long distance away.

7. Much may be learned of the likelihood of formation of line squalls along the trough of a depression through a careful study of temperature distribution along the trough. A drop of several degrees appearing along the trough line on the synoptic chart is usually accompanied by line squalls in the

summer time, especially in the afternoon. A well-defined V-shaped depression with an abrupt wind shift is usually accompanied by squalls and thunderstorms in the summer time, as is well known among weather forecasters.

8. Local thunderstorms do not form when the wind aloft is fresh or strong. If reports of the upper air show strong winds aloft over a large region, this strong upper air current is not likely to die out for several hours at least, and therefore the probability of a local thundershower is slight.

9. Long study of local conditions reveals certain types of weather distribution which although calling for a thundershower forecast for the general region or district, do not usually result in thundershowers in the particular locality in which the forecaster is interested. With other types, a local thundershower usually occurs when the forecast for the district does not call for them. These rules like other rules for forecasting from the synoptic chart are difficult to analyze and classify. They are opinions based on long experience in the locality rather than "cut and dried" rules. Nevertheless they are valuable in local forecasting.

10. A method used with some success in forecasting local squalls and thundershowers in the trade wind region is to arrange for reports of the location and size of showers passing stations or ships to windward of the forecaster's locality. The fairly constant direction of the trade wind at cloud altitude enables the forecaster to determine whether the shower will pass over his station or not, and the velocity of the trade wind at cloud altitude serves as a basis for an estimate of how long it will take the shower to reach the station.

11. A careful study of pilot balloon soundings and the relation of upper wind to subsequent weather reveals certain conditions which serve as indications of approaching weather during the following few hours. The indications are mostly of local value only, consequently a statement of them is not of general interest. As an example, along the Virginia coast the

upper winds sometimes serve as an indication of the formation of rain which is uncertain from the weather map alone. In cases where northeast surface winds underrun westerly winds aloft, if the sounding shows a well-marked boundary between these currents and if the velocities of each are moderate to fresh or higher, rain usually develops along the coast within a few hours.

C. Tendency of the wind when light and when the pressure gradient does not indicate a general increase in wind.

12. The wind decreases rapidly in velocity and gustiness towards sunset, but after it drops below 10 miles per hour its further change is uncertain. If the temperature continues to fall and the humidity to rise, both velocity and gustiness will continue to decrease, but if the temperature and humidity remain stationary the velocity of the wind will alternately rise and fall and the gustiness remain considerable. In the case of southerly winds with a depression to the west, the winds will decrease as long as the temperature falls, hold when the fall is checked and increase as the temperature rises. All of these conditions are more noticeable in the warm months, but they remain positive during cold months.

13. An indication of which way the wind will shift during the next few hours is afforded by the Dines Anemobiagraph. By watching the velocity and direction pens at the same time, the direction from which the strongest gusts occur is the direction toward which the general wind will turn. In case this direction is in opposition to that indicated by the weather map, this shift will be temporary only. The Dines will again tell when another shift is approaching.

D. Sinuosities in isobars.

14. On the U. S. Weather Maps the stations are in general too far apart to enable one to find all important sinuosities in the isobars which will pass over the locality in which the forecaster is interested. But many of the larger sinuosities may

be identified. They are all associated with wind and cloud conditions different from those in the neighboring districts where the isobars are regular. Occasionally a cloudy condition occurs when the map indicates only fair weather to the casual observer. However, a closer scrutiny of the map often shows an irregularity in the pressure which does not appear in the isobars drawn only for every tenth of an inch of atmospheric pressure. This is useful when it is important to know the exact weather for a coming period and very unexpected clouds appear. Very marked irregularities in summer time will result in thunderstorms. Those less marked are accompanied, whatever the season, by light precipitation. Very minor irregularities produce only clouds. Such clouds assemble usually with a sharp, extended edge and move as one mass, ending in the same manner. At times the barograph will show a slight movement at the beginning and ending of these conditions, but only in the case of the more pronounced irregularities. A micro-barograph will show a fluctuation in nearly all cases, but not in advance, only at the time of actual occurrence. At the same time changes in wind direction and velocity occur.

15. Closely allied to the above indication is the fact that when the winds are light, especially at night, they will increase both in velocity and gustiness when such a cloud bank moves in. If the bank is of considerable extent, and the map flat, they will decrease again and remain so until the clouds pass beyond the observer. Then the winds become irregular again and remain so until the major portion of the sky is again clear. This may happen several times during one night.

Weather proverbs. Long before the development of organized meteorological services men engaged in pursuits whose success depended largely upon the weather, noted the sequence of certain signs and indications and the changes in wind and weather that followed. In many cases they expressed these in poetic form as "weather proverbs" or "maxims."

Some of these are purely local in application and others are based upon mere coincidence, such as the fiction that a rainy St. Swithin's Day is followed by a rainy period of 40 days. Many others, however, are of more or less universal application and have stood the test of critical analysis. In a recent publication [4] Humphreys has collected the proverbs of this sort and has provided for each its physical explanation. Only a few of most interest to the aeronaut can be given here. For others and for the explanation of all of them the reader is referred to the work above cited.

Sky red in the morning
Is a sailor's sure warning;
Sky red at night
Is the sailor's delight.

Evening red and morning gray
Help the traveler on his way;
Evening gray and morning red
Bring down rain upon his head.

A rainbow in the morning
Is the shepherd's warning;
A rainbow at night
Is the shepherd's delight.

The higher the clouds, the finer the weather.

Mackerel scales and mares' tails
Make lofty ships carry low sails.

Whene'er the clouds do weave
'Twill storm before they leave.

Rain long foretold, long last;
Short notice, soon past.

[4] Humphreys, W. J., "Weather Proverbs and Paradoxes," Williams and Wilkins Co., Baltimore, 1923.

When the morn is dry
The rain is nigh.
When the morn is wet
No rain you get.

A veering wind, fair weather;
A backing wind, foul weather.

CHAPTER X

FLYING OVER THE NORTH ATLANTIC AND IN THE NORTH POLAR REGIONS

North Atlantic

Information concerning surface meteorological conditions in the North Atlantic is fairly complete for the regions of greatest travel, less so for others. Free-air data are too meager even for general conclusions, but some inferences are possible from observations above land surfaces at about the same latitudes, providing the relative effects of land and water on the distribution of meteorological elements are kept in mind. There follows a brief summary of a study made in 1919 in preparation for the trans-Atlantic flight of the NC seaplanes.[1]

Fog. One of the most serious obstacles to trans-Atlantic flight appears to be the large percentage of days on which fog occurs, particularly near the American coast. This amounts in the regions southeast and east of Newfoundland to about 60 per cent in summer and about 20 to 35 per cent in winter, the frequency in the latter season being greatest to the southeast. Near the Irish coast it varies from about 10 per cent in summer to 5 per cent in winter. Fogs rarely occur near the Azores or between them and Portugal. In general the Newfoundland fogs occur as the result of warm moisture-laden winds blowing from the Gulf Stream regions over the colder waters of the Labrador Current.

Height of fog. There is every reason to believe that above the sea in the great majority of cases fogs extend to a low

[1] Gregg, W. R., "Trans-Atlantic Flight from the Meteorologists' Point of View," *Monthly Weather Review,* Vol. 47, pp. 65-75, February, 1919.

altitude only. This is clearly shown in the kite records obtained on the *Scotia* and on the *Seneca.* The top of the fog is very definite, and above it the relative humidity decreases rapidly. The temperature usually increases from the surface to the top of the fog and decreases above it. Out of nine kite records in fog obtained on the *Scotia* only one showed fog extending to a height greater than 300 meters, the average being about 150 meters. The one exception was due to long-continued blowing of warm air over successively colder areas, but, even in this case the top of the fog was at a height of less than 900 meters. Ten kite flights in fog were made from the deck of the *Seneca,* and the temperature gradients indicate that in only one did the fog extend to a height greater than 250 meters. In the one exception it is impossible to give the exact height of the fog, as no humidity values were obtained; but the temperature record indicated an altitude of about 950 meters. Additional testimony from local observers, in support of these conclusions, is contained in a report of the British Civil Aerial Transport Committee, published in 1918.

Winds. On the average winds in summer are from a west-southwesterly direction, with a mean velocity of 8 m. p. s., at all points along the northern route; in winter they are westerly, with a slight north component, i.e., a component *from* the north, mean velocity about 10 m. p. s., from Newfoundland to longitude 45° W. Farther east they have a strong south component, becoming southwesterly near the British Isles. The mean velocity along this section of the course is 10 to 15 m. p. s., being highest between longitudes 45° and 20°W. Over the southern course winds in summer are southwesterly, 8 m. p. s., to longitude 40°W; westerly, 10 to 12 m. p. s., thence to the Azores; and west-southwesterly, 10 m. p. s., between the Azores and Portugal. The percentage of winds from a westerly direction, i.e., between north-northwest and south-southwest, varies along the northern route from about

85 in winter to 70 in summer; near the Azores, from 75 to 65; and from the Azores to Portugal, 40 to 30. In the last-named region winds from all directions are about equally frequent in winter, but in summer northerly winds predominate.

Gales. Practically all of the cyclonic disturbances that move across the United States, no matter what their place of origin, enter the North Atlantic Ocean slightly to the south of Newfoundland, moving thence east-northeastward toward the Iceland Low, and thus crossing the northern route roughly between longitudes 30° and 40°W. These storms vary considerably in size, intensity, and rate of travel. In general, they are larger and travel more slowly over the ocean than over the continents. They are, moreover, more frequent, more intense and faster moving in winter than in summer. In their movements across the Atlantic, the more intense cyclones are often accompanied by gales having a velocity of more than 20 m. p. s., the directions of these gales depending upon the part of the storm in which the observations are made. Thus, considering a typical case, viz., a well-developed low leaving New England and passing south and eventually east of Newfoundland, we should expect to have at the latter place gales successively from the east, northeast, north, northwest, and west. Along the Ireland route the percentage of days on which such gales occur varies in general from about 25 in winter to 5 in summer. In winter they are often accompanied by violent snow squalls. From Newfoundland to the Azores the percentage frequency of gales is about 20 in winter and 3 in summer; from the Azores to Portugal, about 7 and 1, respectively.

For the same pressure gradient surface wind speeds are greater at sea than on land owing to the smaller effects of friction. The gradient wind, however, i.e., that at about 500 meters, is the same in both cases, from which it is seen that the increase in speed with altitude is much less at sea than on

land. Similarly, and for the same reason, the turning of the wind with altitude is less. At great heights the velocity is probably less on the average than over the continents because of the smaller temperature gradient from south to north. Especially is this true in the winter half of the year.

Turbulence. Flying conditions in the eastern Atlantic are much better than on the western side not only because there is less fog but also because the air is more stable. Above the border line between the Gulf Stream and the Labrador Current considerable "bumpiness" was experienced by the NC planes and by the R-34, in some cases extending to 2 or 3 kilometers.

Flying routes. An examination of 10 years' marine weather maps indicated that at an altitude of 500 to 1,000 meters conditions are favorable for eastward flight approximately one-third of the time; at greater altitudes the percentage of favorable days materially increases. For westward flight the percentage of favorable days is so small as to make trans-Atlantic flying in this direction impracticable until the cruising radius of aircraft is increased to such an extent that they are relatively independent of wind conditions. They could then adopt one of two courses: (1) Use the southern route, Portugal to Lesser Antilles, about 3,600 miles, as a permanent highway; or (2) the northern route, Ireland to Newfoundland, about 1,900 miles, varying the course from day to day according to the pressure distribution prevailing. In the first case flying conditions would be favorable most of the time, with fair weather and tail winds, but the great length of this route would be a severe handicap and there would still be a considerable distance to go after reaching the Lesser Antilles. In the second case it would occasionally be possible to fly a straight course, but as a rule it would be necessary to vary it somewhat. This is not so serious a matter as might at first be supposed, providing there is sufficient reserve power. The

following comments by Major G. H. Scott (of R-34 fame) and Lieut. Col. V. C. Richmond are pertinent.[2]

"A pilot on meeting a strong wind, turns broadside on to the wind, and in a very short time he will be through the bad zone and in a light or favourable wind. It will be seen that the time taken for a ship to cross the bad weather zone does not depend on the strength of the wind but upon the speed of the ship; also that the amount the ship drifts out of its course depends, on the other hand, on the time taken and the speed of the wind. The airship must, of course, have a sufficient air speed to prevent its being driven too far out of its course.

"Except in very rare circumstances, such as when the base at which the pilot wishes to land is in the bad weather zone, a pilot should never beat directly into a strong wind, and even in the above case it often pays to lie off for a few hours, as the movement of the center of the depression will move the area of strong wind away from the base.

"It is owing to this movement of the center of a depression that, except in exceptional circumstances, a very strong wind does not blow for very long in one place.

"A much more difficult wind for the airship pilot to deal with is a head or beam wind of from 20 to 30 miles per hour, as this may blow over a comparatively large area and for long periods.

"In order to deal with this wind, good meteorological reports must be at the pilot's disposal, and he must vary his course sometimes 12 to 24 hours ahead in order to circumvent such a wind. As an example, the pilot is flying from Malta to Norfolk; there is a large depression centered N. W. of Scotland, giving a westerly and southwesterly wind over the south of England and north of France. If the pilot endeavored to make good a direct course from Malta to England he would be

[2] "Detailed Consideration of the Effect of Meteorological Conditions on Airships," *Journal of the Royal Aeronautical Society,* March, 1924, pp. 189-221.

obliged to edge up into a 30-mile broadside wind over several hundred miles, and the time taken for the journey would be greatly increased.

"If, however, the pilot was supplied with good meteorological information, he would set his course so as to pass out into the Bay of Biscay, just north of the Pyrenees, and when he encountered westerly winds of increasing force he would turn north at right angles to the wind and use the drift to make his base. Thus during no part of his journey would he be heading into a wind, and although the course taken is somewhat longer than the direct route, the time taken will be very little in excess of the still-air time, and with a reasonable amount of spare engine power the airship could still make its scheduled time on the journey."

North Polar Regions

Meteorological information for the regions along the margin of the north polar zone is fairly complete, but little is known as to conditions above latitude 80°. Only a brief general statement can be made at this time. Somewhat detailed discussions are contained in Hann's "Handbuch der Klimatologie," Vol. 3, pp. 588-677, 1911 ed.; and in Ward's "Climate," pp. 151-177, 1918. Additional data may be found in the *Arctic Pilot,* H. O. 137; *Arctic Pilot,* Hydrographic Dept., B. A.; Bartholomew's "Physical Atlas," Vol. 3; *Nautical Meteorological Annual of the Danish Meteorological Institute;* and the reports of Greely, Peary, Stefansson and others.

Temperature. From all available data, H. Mohn[3] has deduced the following mean temperatures, in °C., for different latitudes:

[3] In *Meteorologische Zeitschrift,* 1906, p. 47.

Latitude, N	60°	65°	70°	75°	80°	85°	90°
January	– 16.1	– 23.0	– 26.3	– 29.0	– 32.2	– 38.1	– 41
April	– 2.8	– 7.3	– 14.0	– 18.8	– 22.7	– 26.5	– 28
July	14.1	12.4	7.3	3.4	2.0	0.3	– 1
October	0.3	– 4.1	– 9.3	– 14.1	– 19.1	– 22.2	– 24
Year	– 1.1	– 5.8	– 10.7	– 14.7	– 18.1	– 21.2	– 22.7

In winter the prevailing tendency for temperatures to decrease with increasing latitude is broken by two areas of extreme cold in northern Siberia and in northern Greenland, where the average is lower than at the pole itself; in summer the region in Siberia is warmer than any other at the same latitude.

Observations at Fort Conger, Grinnell Land (lat. 82°N., long. 65°W) during 1881-1883 gave as the highest temperature 12°C., and the lowest –52°C. In Franz Joseph's Land about the same latitude but in *east* longitude between 50° and 67°, several series of observations by different expeditions showed a maximum of 12°C. and a minimum of –46°C. Lowest temperatures usually occur in calm weather as a result of active radiation. It seems likely that on such occasions there is an inversion above the surface, as a wind almost invariably raises the temperature appreciably.

Winds. The cyclones of temperate latitudes in many instances reach and travel along the margin of the polar zone but seldom very far within it. Hence, the winds at high latitudes are prevailingly from an easterly direction. Thus, the Franz Joseph's Land data for 1894-1896 show NE to SE winds 39 per cent of the time, a high value in view of the fact that calms prevailed 27 per cent of the time. At Fort Conger the wind for the year averaged about S65°E, with a slight N component in winter and a strong S component in summer. Here also the percentage of calms was high, 35 per cent, with a marked seasonal variation from less than 5 per cent in summer to about 75 per cent in winter. Gales

were apparently not frequent at this place, although there was one case of 60 m. p.h. from the northeast and another of 52 from the southwest, both in winter. The average velocity was somewhat greater in summer than in winter owing to the preponderance of calms in the latter season.

Farther south, i.e., near the margin of the polar zone, gales and stormy weather are much more frequent in winter owing to the influence of cyclonic disturbances.

Weather. Precipitation occurs mostly in the form of fine, dry snow and its water equivalent is probably less than 10 inches a year as a rule. At Fort Conger it averaged 6. Cloudiness is much less than in temperate latitudes, with a maximum in summer and a minimum in winter. In the latter season clear weather prevails at times for a week or more. Stratus is the most common type in summer and this frequently develops from fog which is quite prevalent, especially along the border line between land and water areas or in the vicinity of ice packs. Fogs seldom occur in winter and, when they do, are of the radiation type and therefore shallow.

APPENDIX I

DISTRIBUTION OF WEATHER FORECASTS BY RADIO

Aviation bulletins. Radio broadcasts of weather information, forecasts and warnings for the special benefit of marine and aviation interests are issued twice daily, at 10:30 A. M. and 10:30 P. M., 75th meridian time, from Arlington, Va., (NAA), by the Office of Communications of the Navy Department. The bulletins are sent on a wave-length of 2,655 meters cw., and invariably begin with the words, "Weather Bureau Bulletin."

The bulletin is divided into two parts. The first part is in code and contains surface and free-air data for selected stations in the United States and Southern Canada. One or more "key-letters" are used to indicate the names of the stations, e.g., "SE" for Seattle, Wash.; "NY" for New York, N. Y., etc., and these are followed by one or more five-unit groups of figures. The first group gives the barometric pressure reduced to sea-level and expressed in three figures; and the wind direction and force (Beaufort Scale) each in one figure. The second group gives the state of weather expressed in one figure; the barometric tendency (rise or fall in hundredths of an inch during 2 hours immediately preceding the observation) expressed in one figure; past weather during the preceding 12 hours expressed in one figure; and current temperature expressed in two figures. The third group gives the prevailing upper clouds and direction each in one figure; the prevailing lower clouds and direction each in one figure; and amount of lower clouds expressed in one figure. Cloud reports are not received from all stations in the bulletin and therefore this

group may be omitted; also when the weather is clear, or sky cloudless. For certain other stations other groups of figures contain free-air wind directions and velocities, as determined from balloon ascensions, the number of groups depending upon the height reached by the balloons. The first figure in each of these extra groups indicates the number of the group: 4th, 5th and so on. The next two figures give the wind direction and force at a certain level and the last two figures give the same data for the next higher level. The altitudes for the groups are: 4th, 250 and 500 meters; 5th, 1,000 and 1,500; 6th, 2,000 and 3,000; and 7th, 4,000 and 5,000. The last group gives data for the highest altitude reached; the first figure (8) identifies the group as the one showing the maximum altitude, and it may be the 4th, 5th, 6th or 7th groups depending upon the actual altitude reached; the 2d and 3d figures indicate the altitude in hundreds of meters, and the 4th and 5th, the wind direction and force at that altitude.

When free-air observations are not possible because of dense fog, rain or snow, the word FOGGY, RAIN or SNOW is sent instead of the fourth group. When data for any portion of a group are missing, the letter X is substituted for each missing figure.

The second part of the bulletin is in plain language and consists of: A synopsis of general pressure distribution; wind and weather forecasts for marine interests; and flying weather forecast for each of 7 zones (see Figure 33).

Similar bulletins for the west coast are broadcast from San Francisco Naval Radio Station (NPG), at 12 noon, 75th meridian time on a wave-length of 7,005 meters cw.; and at 10:30 P.M., 75th meridian time, on wave-lengths of 7,005 meters cw. and 2,607 meters cw., simultaneously (9:00 A. M. and 7:30 P. M. Pacific local time, respectively). Stations from which reports are furnished are those in the Pacific coast and Rocky Mountain states, southwestern Canada, Alaska, Hawaii,

Guam, Manila, China and Japan. Flying weather forecasts are made for zones 12 to 14 (see Figure 33).

Surface weather forecasts. In addition to the special aviation bulletins above briefly outlined, forecasts of weather, temperature and winds, including storm warnings, are broadcast from a large number of points by radio telegraph. The character of these broadcasts varies according to the needs of the regions concerned. Thus, there is a special service for the benefit of navigation on the Great Lakes, another for the Gulf of Mexico and the Caribbean Sea and others for the Atlantic and Pacific coasts.

Finally, there is the purely local distribution of state and local forecasts by radio-phone from a large proportion of cities in which Weather Bureau stations are located and from other points. The schedules, wave-lengths, etc., are still subject to more or less change, so that a list now effective would soon be out of date. It is an easy matter, however, at any time to obtain information on these points by merely communicating with the Central Office at Washington, D. C., or, for local bulletins only, with the nearest Weather Bureau station. A list of the stations in the United States, as of July 1, 1925, follows:

Weather Bureau Stations in the United States

Abilene, Tex.
Albany, N. Y.
Alpena, Mich.
Amarillo, Tex.
Anniston, Ala.
Apalachicola, Fla.
Asheville, N. C.
Atlanta, Ga.*
Atlantic City, N. J.
Augusta, Ga.
Baker, Oreg.
Baltimore, Md.*
Binghamton, N. Y.
Birmingham, Ala.
Bismarck, N. Dak.*
Block Island, R. I.
Boise, Idaho.*
Boston, Mass.*
Broken Arrow, Okla.†
Brownsville, Tex.

Forecast centers in bold-faced type.
*Climatological section center.
†Aerological station.

Buffalo, N. Y.
Burlington, Vt.†

Cairo, Ill.
Canton, N. Y.
Cape Henry, Va.
Cape May, N. J.
Charles City, Iowa.
Charleston, S. C.
Charlotte, N. C.
Chattanooga, Tenn.
Cheyenne, Wyo.*
Chicago, Ill.
Cincinnati, Ohio.
Cleveland, Ohio.
Columbia, Mo.*
Columbia, S. C.*
Columbus, Ohio.*
Concord, N. H.
Concordia, Kans.
Corpus Christi, Tex.

Dallas, Tex.
Davenport, Iowa.
Dayton, Ohio.
Del Rio, Tex.
Denver, Colo.*†
Des Moines, Iowa.*
Detroit, Mich.
Devils Lake, N. Dak.
Dodge City, Kans.
Drexel, Nebr.†
(P. O. Washington, Nebr.)
Dubuque, Iowa.
Due West, S. C.†
Duluth, Minn.

Eastport, Me.
Elkins, W. Va.
Ellendale, N. Dak.†
El Paso, Tex.
Erie, Pa.
Escanaba, Mich.
Eureka, Calif.
Evansville, Ind.

Fort Smith, Ark.
Fort Wayne, Ind.
Fort Worth, Tex.
Fresno, Calif.

Galveston, Tex.
Grand Haven, Mich.
Grand Junction, Colo.
Grand Rapids, Mich.
Green Bay, Wis.
Greenville, S. C.
Groesbeck, Tex.†

Hannibal, Mo.
Harrisburg, Pa.
Hartford, Conn.
Hatteras, N. C.
Havre, Mont.
Helena, Mont.*
Honolulu, Hawaii.*
Houghton, Mich.
Houston, Tex.*
Huron, S. Dak.*

Indianapolis, Ind.*
Iola, Kans.
Ithaca, N. Y.*†

Jacksonville, Fla.*
Juneau, Alaska.*

Kalispell, Mont.
Kansas City, Mo.
Keokuk, Iowa.
Key West, Fla.†
Knoxville, Tenn.

La Crosse, Wis.
Lander, Wyo.
Lansing, Mich.*†

Forecast centers in bold-faced type.
*Climatological section center.
†Aerological station.

Lewiston, Idaho.
Lexington, Ky.
Lincoln, Nebr.*
Little Rock, Ark.*
Los Angeles, Calif.
Louisville, Ky.*
Ludington, Mich.
Lynchburg, Va.

Macon, Ga.
Madison, Wis.†
Manteo, N. C.
Marquette, Mich.
Memphis, Tenn.†
Meridian, Miss.
Miami, Fla.
Miles City, Mont.
Milwaukee, Wis.*
Minneapolis, Minn.*
Mobile, Ala.
Modena, Utah.
Montgomery, Ala.*
Moorhead, Minn.

Nantucket, Mass.
Nashville, Tenn.*
New Haven, Conn.
New Orleans, La.*
New York, N. Y.
Norfolk, Va.
Northfield, Vt.
North Head, Wash.
(P. O. Ilwaco, Wash.)
North Platte, Nebr.

Oklahoma City, Okla.*
Omaha, Nebr.
Oswego, N. Y.

Palestine, Tex.
Parkersburg, W. Va.*
Pensacola, Fla.
Peoria, Ill.
Philadelphia, Pa.*
Phoenix, Ariz.*
Pierre, S. Dak.
Pittsburgh, Pa.
Pocatello, Idaho.
Point Reyes, Calif.
(Through San Francisco Sta.)
Port Angeles, Wash.
Port Arthur, Tex.
Port Huron, Mich.
Portland, Me.
Portland, Oreg.*
Providence, R. I.
Pueblo, Colo.

Raleigh, N. C.*
Rapid City, S. Dak.
Reading, Pa.
Red Bluff, Calif.
Reno, Nev.*
Richmond, Va.*
Rochester, N. Y.
Roseburg, Oreg.
Roswell, N. Mex.
Royal Center, Ind.†

Sacramento, Calif.
St. Joseph, Mo.
St. Louis, Mo.
St. Paul, Minn.
Salt Lake City, Utah.*
San Antonio, Tex.
San Diego, Calif.
Sandusky, Ohio.
Sandy Hook, N. J.
(P. O. Fort Hancock, N. J.)
San Francisco, Calif.*†
San Jose, Calif.
San Juan, Porto Rico, W I.*†
San Luis Obispo, Calif.
Santa Fe, N. Mex.*
Sault Sainte Marie, Mich.
Savannah, Ga.
Scranton, Pa.
Seattle, Wash.*

Forecast centers in bold-faced type.
* Climatological section center.
†Aerological station.

Sheridan, Wyo.
Shreveport, La.
Sioux City, Iowa.
Spokane, Wash.
Springfield, Ill.*
Springfield, Mo.
Syracuse, N. Y.

Tacoma, Wash.
Tampa, Fla.
Tatoosh Island, Wash.
Taylor, Tex.
Terre Haute, Ind.
Thomasville, Ga.
Toledo, Ohio.
Topeka, Kans.*
Trenton, N. J.*

Valentine, Nebr.
Vicksburg, Miss.*
Wagon Wheel Gap, Colo.‡
(Through Denver Sta.)
Walla Walla, Wash.
Washington, D. C.†
Wausau, Wis.
Wichita, Kans.
Williston, N. Dak.
Wilmington, N. C.
Winnemucca, Nev.
Wytheville, Va.

Yankton, S. Dak.
Yellowstone Park, Wyo.
Yuma, Ariz.

Forecast centers in bold-faced type.
* Climatological section center.
† Aerological station.
‡ Forest Experiment Station; maintained in co-operation with Forest Service.

APPENDIX II

METEOROLOGICAL SERVICES OF THE WORLD

The following list gives the addresses of headquarters or central offices of the official meteorological services of the world and a few leading independent meteorological observatories. They are given in alphabetical order of the countries concerned, except that those for Africa and the West Indies are in groups for those regions as a whole.

Service Météorologique d'Algérie, l'Université, Algiers, **Algeria.**
Meteorological Observatory, Sao Paulo de Loando, **Angola,** Africa.
Controller, Physical Department, Dawawyn Post Office, Cairo, **Egypt.**
Observ. Campos Ridrigues, P. O. Box 256, Lourenço Marques, **Portuguese East Africa.**
Observatoire Royal, Tananarivo, **Madagascar.**
Observatory, Bulawayo, **Rhodesia,** South Africa.
Chief Meteorologist, Dept. Irrigation, P.O.Box 309, Pretoria, **South Africa.**
Osservatorio Meteorologico, **Tripoli,** Libya, Africa.
Director General, Service Météorologique, **Tunis,** Africa.
Oficina Meteorológica, Paseo Colon 974, Buenos Aires, **Argentina.**
Commonwealth Bureau of Meteorology, Melbourne, **Australia.**
Zentralanstalt für Meteorologie und Geodynamik, Hohe Warte 38, Vienna, **Austria.**
Institut Royal Météorologique, Uccle, **Belgium.**
Directoria de Meteorologia, Palacio dos Estados, 4.o andar, Rio de Janeiro, **Brazil.**
Director, Meteorological Service, Toronto, **Canada.**
Surveyor-General, Colombo, **Ceylon.**
Instituto Meteorológico, Casilla 717, Santiago, **Chile.**
Royal Observatory, Hongkong, **China.**
Meteorological Observatory, Tsingtau, **China.**
Observatoire Météorologique, Zi-ka-wei, near Shanghai, **China.**

Observatoire Central Météorologique, Phu-Lien near Haiphong, Tonkin, **Indo-China.**

Observatorio S. Bartolomé, Apartado 270, Bogota, **Colombia.**

Meteorological Institute, Prague, II U Karlova, **Czechoslovakia.**

Meteorologisk Institut, Copenhagen, **Denmark.**

Meteorological Office, Air Ministry, Kingsway, London, W. C. 2, **England.**

Valtion Meteorologinen Keskuslaitos, Helsingfors, **Finland.**

Office National Météorologique, 176 Rue de l'Université, Paris VII, **France.**

Institut de Physique du Globe, 38, Boulevard d'Anvers, Strasbourg, **France.**

Meteorologisches Observatorium, Aachen, **Germany.**

Aeronautisches Observatorium, Lindenberg, Kr. Beeskow, **Germany.**

Preussisches Meteorologisches Institut, Schinkelplatz 6, Berlin, W., **Germany.**

Hessisches Landesamt für Wetter und Gewässerkunde, Darmstadt, **Germany.**

Landes-Wetterwarte, Grosse Meissnerstr, 15, Dresden N 6, **Germany.**

Deutsche Seewarte, Hamburg, **Germany.**

Badische Landeswetterwarte, Durlacher Allee 56, Karlsruhe, **Germany.**

B. Landeswetterwarte, Gabelsbergerstr. 55/1, Munich, **Germany.**

Württemberg Statist. Landesamt, Meteorol. Abt., Stuttgart, **Germany.**

Drachenstation, Friederichshafen, Württemberg, **Germany.**

Observatoire National, Athens, **Greece.**

Royal Meteorological and Magnetical Institute, Budapest, **Hungary.**

Loggildingarstofan, Reykjavik, **Iceland.**

Alipore Observatory, Calcutta, **India.**

Meteorological Office, Simla, **India.**

Osserv. Geodinamico e Aerologico, Pavia, **Italy.**

R. Ufficio Centrale di Meteorologia e Geodinamica, Rome, **Italy.**

Central Meteorological Observatory, Tokyo, **Japan.**

K. Magnetisch en Meteorologisch Observatorium, Batavia, **Java.**

Meteorological Bureau, Department of Agriculture, Todlebena Pulvari No. 6, Riga, **Latvia.**

Royal Alfred Observatory, Pamplemousses, **Mauritius.**

Weather Bureau, Office of the Civil Commissioner, Baghdad, **Mesopotamia.**

Observatorio Meteorológico Central, Tacubaya, D. F., **Mexico.**

K. Nederl. Meteorol. Inst., De Bilt near Utrecht, **Netherlands.**

Meteorological Office, Wellington, **New Zealand.**

Geofysisk Institut, Avd B, Bergen, **Norway.**

Meteorologisches Institut, Christiania, **Norway.**

Inst. Météorologique de Pologne, Rue Nowy Swiat, Warsaw, **Poland.**

Observatorio Infante D. Luiz, Lisbon, **Portugal.**

Institutul Meteorologic Central, Bucuresti, **Romania.**

Observatoire Géophysique Central, Leningrad, **Russia.**

Ukrainian Meteorological Service, Sofiskaya 18, Kiev, Ukrainia, **Russia.**

Samoa Observatory, Apia, **Samoa.**

Observatoire Central, Belgrade, **Serbia.**

Servei Meteorologic de Catalunya, C. Urgell 187, Barcelona, **Spain.**

Obs. Central Meteorológico, Apartado 385, Madrid, **Spain.**

Observatorio del Ebro, Tortosa, **Spain.**

Statens Meteorologisk Hydrografiska Anstalt, Stockholm, **Sweden.**

Schweiz Meteorologische Centralanstalt, Zürich, **Switzerland.**

Observatoire de Ksara, Saïd-Nail près Beirut, **Syria.**

U. S. Weather Bureau, Washington, D. C., **U.S.A.**

Blue Hill Observatory, Hyde Park, Mass., **U.S.A.**

Inst. Meteorológico Nacional, Montevideo, **Uruguay.**

Observatorio Cagigal, Caracas, **Venezuela.**

Observatorio Nacional, Casa Blanca, Havana, **Cuba, W.I.**

Oficina Meteorológica, Duarte 33, San Pedro de Marcoris, **Dominican Republic, W.I.**

Observatoire St. Martial, Port-au-Prince, **Haiti, W.I.**

Government Meteorologist, Montego Bay, **Jamaica, W.I.**

APPENDIX III

BIBLIOGRAPHY

The following list is of course very far from complete. It includes the better known general treatises on meteorology and in addition such books and papers as are believed to be of most interest and value in aeronautics. Numerous other papers containing the results of aerological research have been published in the *Monthly Weather Review* and in many cases a limited supply of reprints is available. A list of these, and copies as long as the supply lasts, will be furnished on application to the Chief of the Weather Bureau, Washington, D. C.

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APPENDIX IV

CONVERSION TABLES AND FACTORS

The following conversion factors are taken from the Smithsonian Physical Tables. These factors are correct at 0° C. for mercury (Hg):

1 inch (of Hg)	= 34.533	grams per sq. cm.
	= 0.491174	pounds per sq. in.
1 cm. (of Hg)	= 13.5956	grams per sq. cm.
	= 0.193376	pounds per sq. in.

Detailed tables may be found in "Smithsonian Meteorological Tables," Fourth Revised Edition, 1918. There follow a few of those that are most generally used, together with the conversion factors. The tables cover a range such that any conversion needed in ordinary work may be made either directly or by a change in the decimal point. For example, in the pressure conversion table, 29.2 inches = 741.7 millimeters. (This rule does not apply to the temperature table.)

Pressure

1 inch	= 25.40005	millimeters
	= 33.86395	millibars
1 millimeter	= 0.03937	inch
	= 1.33322	millibars
1 millibar	= 0.02953	inch
	= 0.75006	millimeter

TABLE I.—INCHES INTO MILLIMETERS AND MILLIBARS

Inches	Millimeters					Millibars				
	.00	.02	.04	.06	.08	.00	.02	.04	.06	.08
0.0	0.00	0.51	1.02	1.52	2.03	0.00	0.68	1.35	2.03	2.71
0.1	2.54	3.05	3.56	4.06	4.57	3.39	4.06	4.74	5.42	6.10
0.2	5.08	5.59	6.10	6.60	7.11	6.77	7.45	8.13	8.80	9.48
0.3	7.62	8.13	8.64	9.14	9.65	10.16	10.84	11.51	12.19	12.87
0.4	10.16	10.67	11.18	11.68	12.19	13.55	14.22	14.90	15.58	16.25
0.5	12.70	13.21	13.72	14.22	14.73	16.93	17.61	18.29	18.96	19.64
0.6	15.24	15.75	16.26	16.76	17.27	20.32	21.00	21.67	22.35	23.03
0.7	17.78	18.29	18.80	19.30	19.81	23.70	24.38	25.06	25.74	26.41
0.8	20.32	20.83	21.34	21.84	22.35	27.09	27.77	28.45	29.12	29.80
0.9	22.86	23.37	23.88	24.38	24.89	30.48	31.15	31.83	32.51	33.19
1.0	25.40	25.91	26.42	26.92	27.43	33.86	34.54	35.22	35.90	36.57
1.1	27.94	28.45	28.96	29.46	29.97	37.25	37.93	38.60	39.28	39.96
1.2	30.48	30.99	31.50	32.00	32.51	40.64	41.31	41.99	42.67	43.35
1.3	33.02	33.53	34.04	34.54	35.05	44.02	44.70	45.38	46.05	46.73
1.4	35.56	36.07	36.58	37.08	37.59	47.41	48.09	48.76	49.44	50.12
1.5	38.10	38.61	39.12	39.62	40.13	50.80	51.47	52.15	52.83	53.51
1.6	40.64	41.15	41.66	42.16	42.67	54.18	54.86	55.54	56.21	56.89
1.7	43.18	43.69	44.20	44.70	45.21	57.57	58.25	58.92	59.60	60.28
1.8	45.72	46.23	46.74	47.24	47.75	60.96	61.63	62.31	62.99	63.66
1.9	48.26	48.77	49.28	49.78	50.29	64.34	65.02	65.70	66.37	67.05
2.0	50.80	51.31	51.82	52.32	52.83	67.73	68.41	69.08	69.76	70.44
2.1	53.34	53.85	54.36	54.86	55.37	71.11	71.79	72.47	73.15	73.82
2.2	55.88	56.39	56.90	57.40	57.91	74.50	75.18	75.86	76.53	77.21
2.3	58.42	58.93	59.44	59.94	60.45	77.89	78.56	79.24	79.92	80.60
2.4	60.96	61.47	61.98	62.48	62.99	81.27	81.95	82.63	83.31	83.98
2.5	63.50	64.01	64.52	65.02	65.53	84.66	85.34	86.01	86.69	87.37
2.6	66.04	66.55	67.06	67.56	68.07	88.05	88.72	89.40	90.08	90.76
2.7	68.58	69.09	69.60	70.10	70.61	91.43	92.11	92.79	93.46	94.14
2.8	71.12	71.63	72.14	72.64	73.15	94.82	95.50	96.17	96.85	97.53
2.9	73.66	74.17	74.68	75.18	75.69	98.21	98.88	99.56	100.24	100.91
3.0	76.20	76.71	77.22	77.72	78.23	101.59	102.27	102.95	103.62	104.30
3.1	78.74	79.25	79.76	80.26	80.77	104.98	105.66	106.33	107.01	107.69

Temperature

The formulae for converting centigrade temperatures to Fahrenheit, and Fahrenheit to centigrade, are respectively:

$$°\text{F.} = \frac{9}{5}\,°\text{C.} + 32°$$

$$\text{and } °\text{C.} = \frac{5}{9}\,(°\text{F.} - 32°)$$

$$\begin{aligned} \text{Absolute zero} &= -273\ °\text{C.}, \\ &= -459.4\ °\text{F.} \\ 0\ °\text{C.} &= 32\ °\text{F} \\ &= 273\ °\text{A} \\ 100\ °\text{C.} &= 212\ °\text{F.} \\ &= 373\ °\text{A} \end{aligned}$$

TABLE 2.—FAHRENHEIT INTO CENTIGRADE, AND CENTIGRADE INTO FAHRENHEIT

°F.	°C.									
	0	1	2	3	4	5	6	7	8	9
−70	−56.7	−57.2	−57.8	−58.3	−58.9	−59.4	−60.0	−60.6	−61.1	−61.7
−60	−51.1	−51.7	−52.2	−52.8	−53.3	−53.9	−54.4	−55.0	−55.6	−56.1
−50	−45.6	−46.1	−46.7	−47.2	−47.8	−48.3	−48.9	−49.4	−50.0	−50.6
−40	−40.0	−40.6	−41.1	−41.7	−42.2	−42.8	−43.3	−43.9	−44.4	−45.0
−30	−34.4	−35.0	−35.6	−36.1	−36.7	−37.2	−37.8	−38.3	−38.9	−39.4
−20	−28.9	−29.4	−30.0	−30.6	−31.1	−31.7	−32.2	−32.8	−33.3	−33.9
−10	−23.3	−23.9	−24.4	−25.0	−25.6	−26.1	−26.7	−27.2	−27.8	−28.3
− 0	−17.8	−18.3	−18.9	−19.4	−20.0	−20.6	−21.1	−21.7	−22.2	−22.8
+ 0	−17.8	−17.2	−16.7	−16.1	−15.6	−15.0	−14.4	−13.9	−13.3	−12.8
10	−12.2	−11.7	−11.1	−10.6	−10.0	− 9.4	− 8.9	− 8.3	− 7.8	− 7.2
20	− 6.7	− 6.1	− 5.6	− 5.0	− 4.4	− 3.9	− 3.3	− 2.8	− 2.2	− 1.7
30	− 1.1	− 0.6	0.0	+ 0.6	1.1	1.7	2.2	2.8	3.3	3.9
40	4.4	5.0	5.6	6.1	6.7	7.2	7.8	8.3	8.9	9.4
50	10.0	10.6	11.1	11.7	12.2	12.8	13.3	13.9	14.4	15.0
60	15.6	16.1	16.7	17.2	17.8	18.3	18.9	19.4	20.0	20.6
70	21.1	21.7	22.2	22.8	23.3	23.9	24.4	25.0	25.6	26.1
80	26.7	27.2	27.8	28.3	28.9	29.4	30.0	30.6	31.1	31.7
90	32.2	32.8	33.3	33.9	34.4	35.0	35.6	36.1	36.7	37.2
100	37.8	38.3	38.9	39.4	40.0	40.6	41.1	41.7	42.2	42.8

°C.	°F.									
	0	1	2	3	4	5	6	7	8	9
−50	−58.0	−59.8	−61.6	−63.4	−65.2	−67.0	−68.8	−70.6	−72.4	−74.2
−40	−40.0	−41.8	−43.6	−45.4	−47.2	−49.0	−50.8	−52.6	−54.4	−56.2
−30	−22.0	−23.8	−25.6	−27.4	−29.2	−31.0	−32.8	−34.6	−36.4	−38.2
−20	− 4.0	− 5.8	− 7.6	− 9.4	−11.2	−13.0	−14.8	−16.6	−18.4	−20.2
−10	14.0	12.2	10.4	8.6	6.8	5.0	3.2	+ 1.4	− 0.4	− 2.2
− 0	32.0	30.2	28.4	26.6	24.8	23.0	21.2	19.4	17.6	15.8
+ 0	32.0	33.8	35.6	37.4	39.2	41.0	42.8	44.6	46.4	48.2
10	50.0	51.8	53.6	55.4	57.2	59.0	60.8	62.6	64.4	66.2
20	68.0	69.8	71.6	73.4	75.2	77.0	78.8	80.6	82.4	84.2
30	86.0	87.8	89.6	91.4	93.2	95.0	96.8	98.6	100.4	102.2
40	104.0	105.8	107.6	109.4	111.2	113.0	114.8	116.6	118.4	120.2

Wind Velocity

1 mile per hour = 0.44704 meter per second
= 1.46667 feet per second
= 1.6093 kilometers per hour

1 meter per second = 2.2369 miles per hour
= 3.2808 feet per second
= 3.6 kilometers per hour

1 foot per second = 0.68182 mile per hour
= 0.30480 meter per second
= 1.09729 kilometers per hour

1 kilometer per hour = 0.62137 mile per hour
= 0.27778 meter per second
= 0.91134 foot per second

TABLE 3.—MILES PER HOUR INTO METERS PER SECOND, FEET PER SECOND AND KILOMETERS PER HOUR

m. p. h.	m. p. s.	ft./sec.	Km./hr.	m. p. h.	m. p. s.	ft./sec.	Km./hr.
1	0.4	1.5	1.6	51	22.8	74.8	82.1
2	0.9	2.9	3.2	52	23.2	76.3	83.7
3	1.3	4.4	4.8	53	23.7	77.7	85.3
4	1.8	5.9	6.4	54	24.1	79.2	86.9
5	2.2	7.3	8.0	55	24.6	80.7	88.5
6	2.7	8.8	9.7	56	25.0	82.1	90.1
7	3.1	10.3	11.3	57	25.5	83.6	91.7
8	3.6	11.7	12.9	58	25.9	85.1	93.3
9	4.0	13.2	14.5	59	26.4	86.5	95.0
10	4.5	14.7	16.1	60	26.8	88.0	96.6
11	4.9	16.1	17.7	61	27.3	89.5	98.2
12	5.4	17.6	19.3	62	27.7	90.9	99.8
13	5.8	19.1	20.9	63	28.2	92.4	101.4
14	6.3	20.5	22.5	64	28.6	93.9	103.0
15	6.7	22.0	24.1	65	29.1	95.3	104.6
16	7.2	23.5	25.7	66	29.5	96.8	106.2
17	7.6	24.9	27.4	67	30.0	98.3	107.8
18	8.0	26.4	29.0	68	30.4	99.7	109.4
19	8.5	27.9	30.6	69	30.8	101.2	111.0
20	8.9	29.3	32.2	70	31.3	102.7	112.7
21	9.4	30.8	33.8	71	31.7	104.1	114.3
22	9.8	32.3	35.4	72	32.2	105.6	115.9
23	10.3	33.7	37.0	73	32.6	107.1	117.5
24	10.7	35.2	38.6	74	33.1	108.5	119.1
25	11.2	36.7	40.2	75	33.5	110.0	120.7
26	11.6	38.1	41.8	76	34.0	111.5	122.3
27	12.1	39.6	43.5	77	34.4	112.9	123.9
28	12.5	41.1	45.1	78	34.9	114.4	125.5
29	13.0	42.5	46.7	79	35.3	115.9	127.1
30	13.4	44.0	48.3	80	35.8	117.3	128.7
31	13.9	45.5	49.9	81	36.2	118.8	130.4
32	14.3	46.9	51.5	82	36.7	120.3	132.0
33	14.8	48.4	53.1	83	37.1	121.7	133.6
34	15.2	49.9	54.7	84	37.6	123.2	135.2
35	15.6	51.3	56.3	85	38.0	124.7	136.8
36	16.1	52.8	57.9	86	38.4	126.1	138.4
37	16.5	54.3	59.5	87	38.9	127.6	140.0
38	17.0	55.7	61.2	88	39.3	129.1	141.6
39	17.4	57.2	62.8	89	39.8	130.5	143.2
40	17.9	58.7	64.4	90	40.2	132.0	144.8
41	18.3	60.1	66.0	91	40.7	133.5	146.4
42	18.8	61.6	67.6	92	41.1	134.9	148.1
43	19.2	63.1	69.2	93	41.6	136.4	149.7
44	19.7	64.5	70.8	94	42.0	137.9	151.3
45	20.1	66.0	72.4	95	42.5	139.3	152.9
46	20.6	67.5	74.0	96	42.9	140.8	154.5
47	21.0	68.9	75.6	97	43.4	142.3	156.1
48	21.5	70.4	77.2	98	43.8	143.7	157.7
49	21.9	71.9	78.9	99	44.3	145.2	159.3
50	22.4	73.3	80.5	100	44.7	146.7	160.9

Miscellaneous Conversion Factors

1 foot	= 0.3048 meter
1 meter	= 39.37 inches
	= 3.2808 feet
1 mile	= 1.6093 kilometers
1 kilometer	= 0.62137 mile
1 statute mile	= 0.8684 nautical mile
1 nautical mile	= 6080.2 feet
	= 1.1516 statute miles
1 grain	= 0.06480 gram
1 gram	= 15.432 grains
1 pound	= 0.45359 kilogram
1 kilogram	= 2.2046 pounds
1 cubic foot	= 0.02832 cubic meter
1 cubic meter	= 35.314 cubic feet

1 pound per cubic foot	= 16.018 kilograms per cubic meter
1 kilogram per cubic meter	= 0.06243 pound per cubic foot
1 grain per cubic foot	= 2.2883 grams per cubic meter
1 gram per cubic meter	= 0.4370 grain per cubic foot
1 pound per square inch	= 70.307 grams per square centimeter
1 gram per square centimeter	= 0.01422 pound per square inch

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